Department of Mechanical and Aerospace Engineering

Appraising Low and Ultra-Low Temperature District Heating for an Urban Regeneration Project

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Abstract

District heating is a technology that can improve the security, finances and sustainability of heat supply. It will therefore play a pivotal role in the future Scottish energy system. With falling demand for space heating, traditional approaches to the design of district heating systems are being superseded by low temperature, renewably powered networks: referred to as 4th Generation networks. This thesis investigates the performance of low and ultra-low temperature district heating (ULTDH) networks and appraises options for their use at an urban regeneration project: HALO Kilmarnock. This appraisal is carried out using the simulation software TRNSYS.

Heat demands and available renewable resources at the site are initially assessed. Exploitable resources are identified and quantified. Through a comparison with the site's temporal demand it is found that the River Irvine and a geothermal borehole represent the most substantial and reliable supply options. Provisional low and ULTDH networks are then designed, which derive their heat from these resources. These networks are then modelled on TRNSYS.

Using the models, several analyses are carried out. First the impact of reducing circuit temperatures from 75°C to 55°C is assessed. It is found that the lowest temperature network has the best performance according to the energy, financial and environmental metrics considered. This is due to the lowering of distribution losses and the improved performance of the generating plant, especially its improved coefficient of performance at low return temperatures.

The ULTDH networks, with 45°C supply temperatures, require auxiliary heating plant for domestic hot water production. Two technologies are used for this: electric heating and booster heat pumps. Against all metrics, the booster heat pumps exhibit superior performance. However, when compared to the 55°C 4GDH model, the ULTDH networks rank more poorly. This is due to the additional plant and energy costs arising from the booster technologies.

These results present a strong case for the lowering of district heating temperatures to 4GDH levels; but question the value of further temperature reductions.

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Introduction

Overview

This thesis assesses the opportunities to utilise low and ultra-low temperature district heating networks at an urban regeneration project in Kilmarnock. Although much progress has been made in Scotland with the decarbonisation of electricity, energy for heating requirements is still produced overwhelmingly via the combustion of natural gas, with nearly 80% of households in Scotland using it as the principal heating fuel. The imperative of transforming the basis of energy production from fossil fuel combustion to a sustainable and environmentally benign one, requires the wholescale shifting of heat supply, distribution and use nationally.

The Scottish Government has modest 2020 targets for renewable heat supply when compared to renewable electricity generation: set at 11% of consumption versus 100% of gross consumption, respectively. A core part of its current strategy is the development of district heating networks (DHN) through which it plans to provide 1.5TWh of heat to 40,000 connected homes by 2020. To this end, it has established several schemes and financial packages to encourage the growth of this industry.

District heating networks supply heat produced in local energy generating sites to users across a geographical area via buried pipework. They present the opportunity to use local renewable resources for local demand that may not be exploitable on an individual basis. Through this, the security of energy supply can be enhanced nationally by reducing dependency on overseas imports. Locally, networks can improve security of supply and lower the costs of heating for individual users. In this way, these networks offer an appealing means of navigating the so-called energy trilemma – equity, security, environmentalism – and balancing the competing pressures on energy supply.

Presently, however, the overall design and operation of district heating networks is shifting due to the changing approach towards energy use in society. Reductions in heat demand and the requirements of decarbonisation make the lowering of circuit temperatures desirable. This 4th generation concept of district heating (4GDH) seeks to overcome the issues faced by previous systems. The new networks provide opportunities to utilise previously untapped resources, for example, ambient resources through heat pumps (HPs), geothermally contained energy and waste heat from industrial processes. At the same time, challenges exist with the feasibility of lowering temperatures principally caused by the need to produce domestic hot water (DHW) without the risks of Legionella growth. This is particularly the case with ultra-low temperature district heating which require supplementary heating to produce this service. Similarly, the lessening of heat demand nationally – while the consequence of welcomed efficiency improvements – undermines the financial feasibility of district heating schemes. This is exacerbated by the high capital cost of installing the requisite network infrastructure.

Although district heating schemes can be used as a retrofit supply option to existing buildings, it is more attractive to install them with a new development. The regeneration of ex-industrial sites, existent in many Scottish cities, provides an opportunity to integrate district heating into the initial plans of the development and so avoid unnecessary costs.

The HALO development in the Scottish town of Kilmarnock is such a regeneration scheme. Located on an ex-whiskey bottling plant in the centre of the town, the project will include commercial, residential and recreational spaces. It aims to provide educational and training opportunities to the local population especially in IT and technological areas. As part of its vision, it plans to provide renewable heat to the site via a geothermally powered heat pump.

Project Aim

This project’s principal aim is to assess viable low-carbon system options for the satisfaction of heat demand at the HALO development. There are three specific aims of the project.

1. Determination of the likely heating demand and of all locally available renewable resources;

2. Evaluation of the impact on performance from dropping supply temperatures from traditional levels to 4th generation temperatures

3. Comparison of the relative strengths and drawbacks of dropping temperatures further to ultra-low temperature networks with a focus on the efficiency, carbon content and cost of meeting the sites demand;

4. Investigation of the TRNSYS tool for the modelling and simulation of district heating networks.

Methodology

To evaluate supply options for the HALO development it was necessary to first estimate the heat demands of the site in terms of annual, hourly and peak loads. This is the principal consideration in the sizing of the plant and operational design of any heating system.

As building plans have not been finalised for the project, it was not possible to model the buildings and determine their demand profiles through simulation. In place, an approach using energy benchmarks was used.

To ensure that the benchmarks were appropriate, the Energy Performance Certificates (EPCs) of the Kilmarnock area were analysed to determine representative energy use levels of modern builds in the local area. Having determined the annual usage, these values could be fitted to representative profiles derived from real monitored data.

To meet this demand, an appraisal of local renewable and low-carbon resources was conducted. First, resources were identified via the Scottish Government’s Heat Map and through a review of the local area. Resources for which data did not exist were scoped out. For the remainder, the total heat resource available and the exploitable resource were determined using standard methods. The seasonal variation of the resources was investigated to identify those resources which could provide sufficient heat to meet demand continually throughout the year.

Alongside the demand and resource determination, low and ultra-low temperature district heating (ULTDH) networks were investigated to identify novel and innovative systems. From this, several networks were conceived that were possible for the site. Information was gathered about the likely capital and operational costs of these systems.

Due to the performance requirements of low-temperature networks it was decided to model each network on the system simulator TRNSYS. This allowed detailed control to be applied and the temporal performance of the system to be assessed. Alongside an evaluation of the efficiency, environmental impact and cost of each technology, the potential improvement in performance with changed network parameters was determined.

Structure

Chapter 1 presents a review of literature relevant to this project. It opens by discussing the national energy picture in Scotland which includes the current deployment of renewable heat capacity and renewable heat potential before discussing governmental policy and support mechanisms. This locates district heating developments within the wider context. The chapter then reviews district heating systems: their essential features, history and potential future design. The literature review ends with a look at modelling district heating networks. This includes an introduction to available software, in particular TRNSYS.

In Chapter 2, the HALO project is introduced and details about Kilmarnock town's demographics, buildings and energy use are presented. Following this, an assessment is conducted to determine the annual heating requirements of the site which are used to produce representative demand profiles. The third section of this chapter offers the work conducted to assess the quantity of all renewable resource options available to HALO Kilmarnock. These include: solar, river, deep-geothermal and waste (sewer) water resources.

With the demand and supply determined, Chapter 3 begins by assessing their temporal coincidence. From this, reliable and viable supply options are determined. The remainder of the chapter deals with potential networks for the site. Initially, several network options are presented and discussed. Through scoping, two promising options remain which are taken forward for modelling on TRNSYS. The chapter ends with a discussion of the final TRNSYS models developed.

Chapter 4 contains the main body of results. It starts with an outline of the analyses undertaken and some limitations of TRNSYS. The results for both network types are then presented and discussed in turn. This includes a detailed look at the operation of the models alongside key performance metrics related to performance, running costs and environmental impact.

In Chapter 5, financial analyses are conducted to supplement the performance analyses of Chapter 4. Important capital and operational costs are calculated, and Renewable Heat Incentive Payments are deduced. The chapter closes with the presentation of two financial metrics: the cost of energy and the payback period for each network.

Following the presentation of the main body of results, Chapter 6 presents a discussion on the key findings and the extent to which the aims of the project were met. The best model is then identified for the HALO site. The relative trade-offs associated with lower circuit temperatures than 4GDH are discussed. The use of TRNSYS for such investigations is then appraised. The chapter ends with a selection of areas and questions where potential future work could be undertaken.

Chapter 7 provides the summary conclusions of the project and its key outputs.

Chapter 1: Literature Review

1.1 Heating in Scotland

1.1.1. National Energy Use

The transformation of heat supply from the combustion of fossil fuels to renewable sources constitutes a key element of meeting Scottish climate change targets and providing long-term energy security. In 2015, non-electric heating accounted for 51% (72.4 TWh) of total final energy use (Scottish Government, 2018a). The UK average of heat demand met through electric heating was approximately 8% and so the total energy consumption for heating purposes was approximately 79 TWh in Scotland that year (BEIS, 2018). Although heating consumption has consistently decreased since 2006 (when corrected for temperature effects) the quantity of non-electric, Scottish heat demand met by renewable sources remains amongst the lowest in Europe at roughly 5% (Scottish Government 2018a).

This statistic is in stark contrast to renewable electrical generation which, in 2016, accounted for 19.7 TWh, or 54%, of total gross electrical consumption. This fact is reflected in the capacities of each service, with 9.7GW and 1.7GW installed for electricity and heat, respectively (Scottish Government 2018a). The significant improvement in making the electrical supply more renewable, obscures the overall progress made towards minimising fossil fuels and nuclear power in the energy sector generally. The breakdown of renewable and non-renewable generation by sector for 2016 is presented in Figure 1.1. In this figure, transport has been left as a single sector.

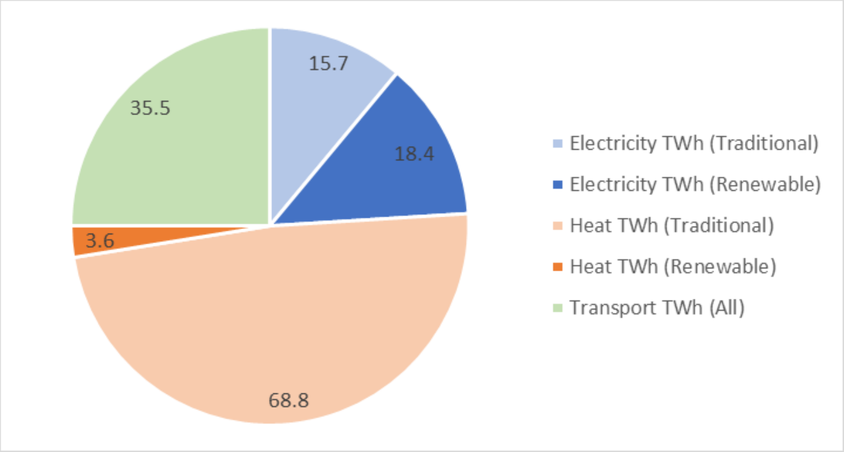


Figure 1.1: Final Scottish energy consumption in 2016 (Scottish Government, 2018a)

Some 43% of heat demand arises from the domestic sector and is met principally through the combustion of natural gas. It is estimated that nearly 4 in 5 residences use this as their primary heating fuel (Scottish Government, 2017b). Although a cheap and easily distributed energy carrier, and the fossil fuel with the lowest carbon content, it is nevertheless a finite resource and one which the UK remains a net importer of. For long-term energy security, equity and sustainability, the reliance on natural gas requires redressing.

1.1.2. Renewable Heat in Scotland

Within renewable heat generation, most of the capacity and output is due to biomass and biomass powered combined heat and power (CHP). Other technologies with lower deployment include: energy from waste (EfW), in the form of incineration, landfill gas and advanced conversion processes; heat pumps; and solar thermal panels (EST, 2017). Biomass heat primarily arises from the combustion of woodchips. Scotland is a producer and net exporter of this fuel. However, concerns exist around the release of entrapped CO_2 in the soil of natural forests, the energy requirements of processing, and the fuel emissions from transportation.

Energy from waste encompasses several technologies that convert landfill and landfill-bound waste into electricity and/or useful heat. Recently, EfW has exhibited the strongest growth in terms of capacity and output across all renewable heat technologies in Scotland. The country has 17 EfW production sites according to the Scottish Environment Protection Agency’s website (SEPA, 2016). Falling levels of household waste and the emissions associated with EfW technologies, call the sustainability of this resource into question.

Heat pumps, which generally consume electricity to transform low-grade heat to higher-grade useful heat, have also seen significant increases in capacity and output of 17% and 21%, respectively, between 2015 and 2016 (EST, 2017). The CO_2 emissions of these technologies are highly dependent on the carbon intensity of the electrical supply. Solar thermal is the smallest contributor in both capacity and output, accounted for under 2% of the Scottish totals in 2016 (EST, 2017). This technology also has the lowest utilisation rate, approximately 6% during the same year, which is due to the limited resource and temporal mismatch between resource availability and heat demand.

The breakdown of output in 2016, by technology and size, is presented in Figure 1.2.

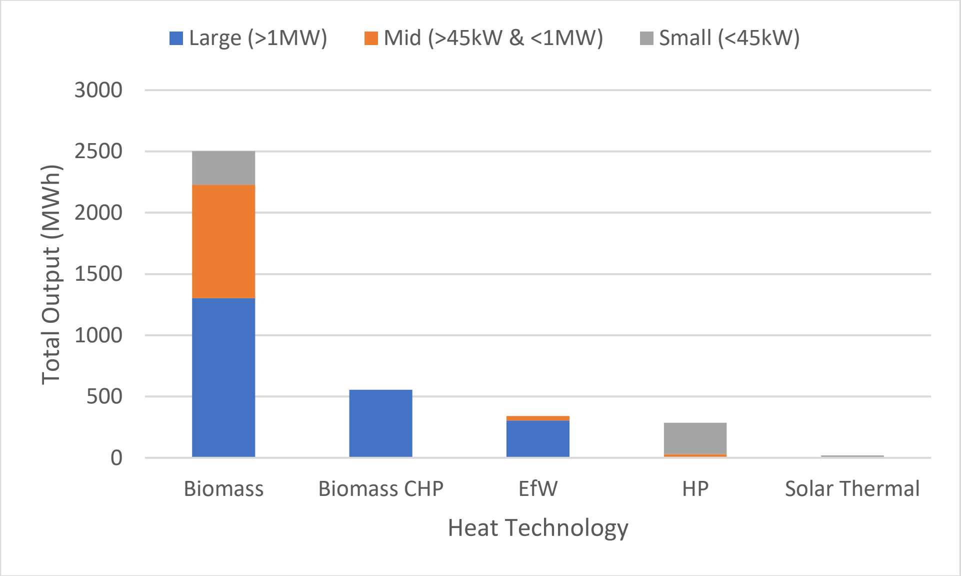


Figure 1.2: Output of renewable heat technologies in 2016 (EST, 2017)

This graph highlights not only the dominance of biomass energy in renewable heat supply, but also the primacy of large (>1MW) installations. Although, only 70 of these installations were recorded, while over 17,500 ‘small’ systems were documented, the former accounts for almost 47% of all heat generated while the latter accounts for 19%. These figures intimate that to achieve heat supply and climate change targets, emphasis ought to be placed on large and mid-capacity generation sites.

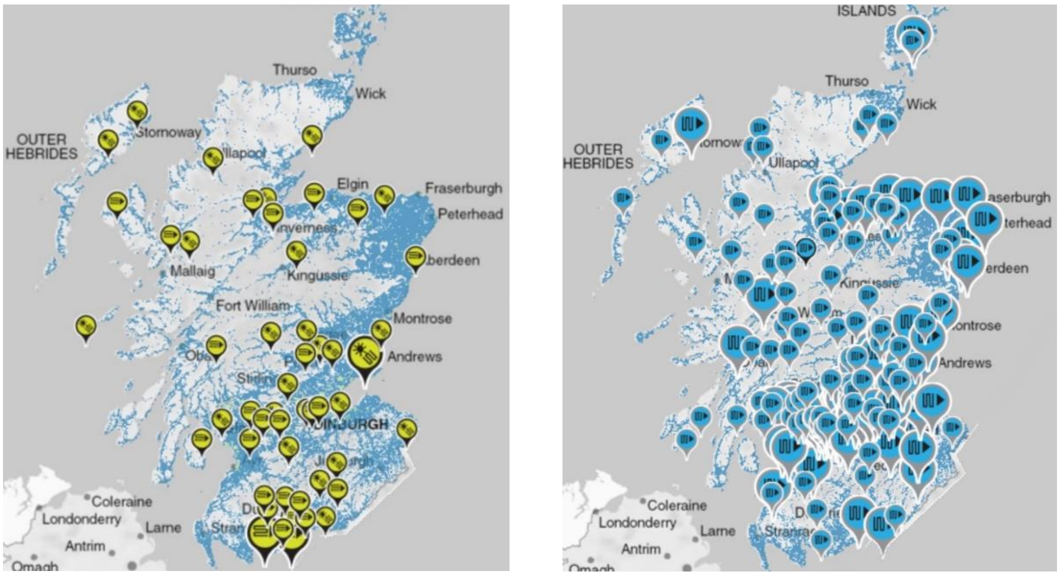
1.1.3. Heat Demand and Resources in Scotland

Most heat demand in Scotland is in the central belt and along the north-east coast where the principal urban areas exist alongside most industry and commerce. The highlands and islands generally have the lowest heat demand due to the low population density of these areas. These regions also have the highest proportion of dwellings not attached to the gas network and so their heating supply is commonly electric or from heating oils (Scottish Government, 2018b). Small renewable heat schemes have proliferated in these areas, serving the needs of individual dwellings or small communities and encouraged by schemes and subsidies such as renewable heat incentive (RHI) payments. It is in the urban areas where attention is required to fundamentally shift the heat supply in Scotland towards a sustainable footing.

To identify and capitalise on potential renewable heat opportunities, the Scottish Executive have developed a heat map of Scotland (Scottish Government, 2018d). This

Geographic Information System tool highlights the heat demand, heat installations and some important heat resources over the country. It provides information on operational, in-development and potential sites for installations. The platform does not contain exhaustive data as it relies on the self-reporting of local authorities, public sector and industry bodies.

A review of air-source heat pump (ASHP) and solar thermal installations revealed approximately 50 medium and large sites as previously defined. The thousands of small installations connected to private properties have been omitted. Nevertheless, the Heat Map indicates a roughly even spread across the country with only slight concentrations in the most urban areas. An image of the distribution is provided in Figure 1.3(a). The Scottish climate is not particularly suited to either technology, with relative low levels of solar radiation and low ambient air temperatures, especially in the peak heating season. It is therefore unlikely that these technologies will have a central role in making heat provision renewable in Scotland.

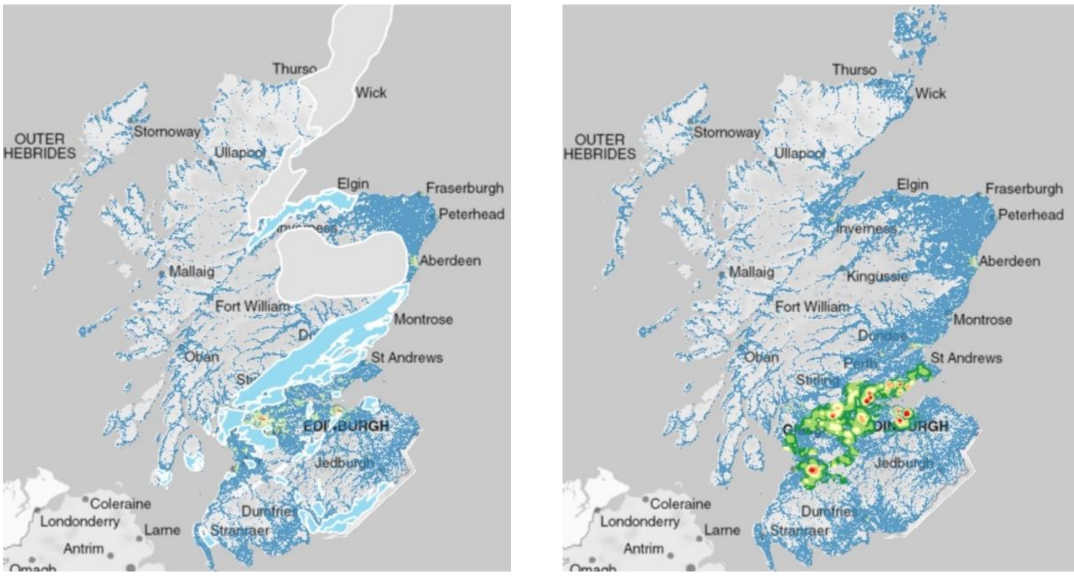

(a) Installed ASHPs and Solar Thermal

(b) WSHP Potential

Figure 1.3: Maps of Scottish renewable heat installations

A plentiful heat resource arises from Scotland’s high levels of precipitation. The rivers this water flows down, and the lochs it collects in, present a potentially unlimited, relatively stable and predictable source of heat. It is estimated that approximately 24% of Scotland’s domestic heat demand is within 1km of a river (Scottish Government, 2018a). Approximately 20% of the Scottish population live with 1km of the coast (CREW, 2012). The potential for water-source heat pumps (WSHP) to provide a substantial portion of domestic demand is significant[i]. The Heat Map supports this suggestion with a near total coverage of the country in potential sites for WSHP developments, presented in Figure 1.3(b).

Another naturally occurring resource is heat contained in the ground. This arises from geothermal activity via radioactive decay in rocks such as granite and the conduction of heat from Earth's mantle. Although geothermal activity is not high in Scotland, there is a significant exploitable resource which has built up over hundreds and thousands of years. The image in Figure 1.4(a), provides the spread of dry hot rocks (grey) and wet hot rocks (light blue) across the country.


(a) Dry and wet hot rocks

(b) Abandoned mine workings

Figure 1.4: Geothermal heat potential map

This separation depends on the geology of the regions and relates to areas with radioactive rock formations and those containing geological aquifers, respectively (Cluff Geothermal Limited, 2013). The former occurs mostly in the north-east while the latter occurs across the Midland belt. The Midland belt is also the region were coal seams have been historically mined. A product of this industry is a substantial heat resource contained within the flooded passageways of now disused mines. The location and depths of these workings are presented in Figure 1.4(b). Due to the industrialisation

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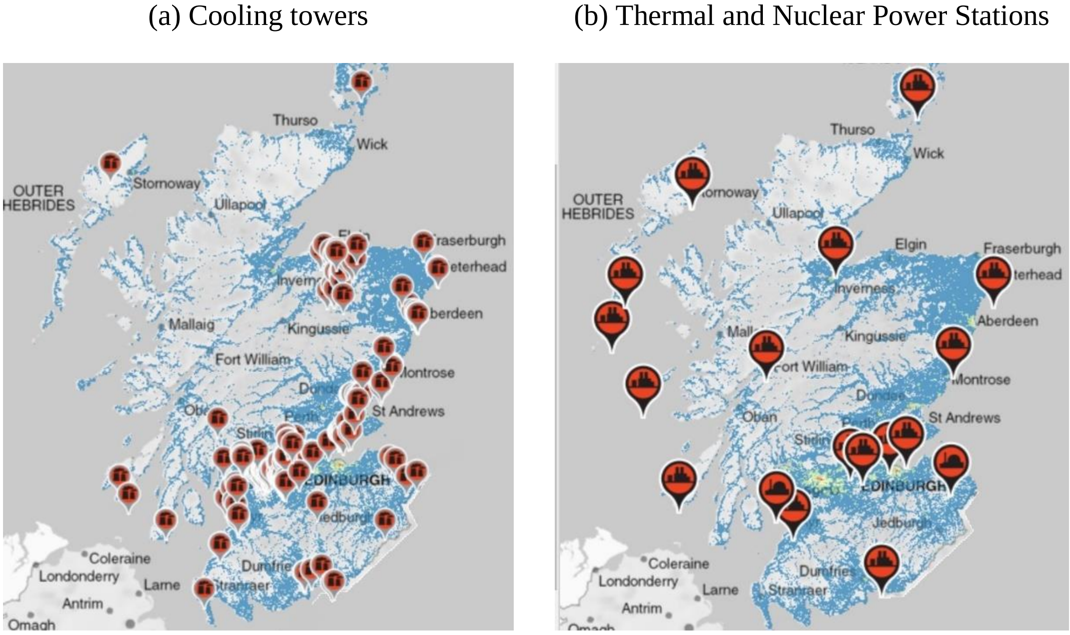
[i] It is noted that a significant overlap of these two statistics is likely to occur due to the large proportion of urban areas situation near the coast and with nearby major rivers.

of Scotland, many urban areas are located near to mine workings. In Glasgow, it has been estimated that this resource could supply 40% of the city's heating requirements for over 100 years (BGS, 2017).

Another heat source with an industrial origin is waste heat generated through power and industrial processes. As before, many of these industries exist near to large urban areas. The distributions of cooling towers and of power plants across Scotland are presented in Figures 1.5(a) and (b) respectively.



(a) Cooling towers

(b) Thermal and Nuclear Power Stations

Figure 1.5: Industrial heat potential map

The financial appeal of sacrificing a portion of heat generated in power stations for heating purposes through heat networks is low in most cases (AEA Technology, 2011). However, the use of the low-grade heat produced from the cooling of the power circuit's water may be more promising.

1.1.4. Government Policy

The key driver for the development of renewable heat and energy in general arises from the energy, efficiency and climate change targets established by the Scottish Government and higher legislative bodies. The Scottish government aims to effectively decarbonise Scottish energy supply by 2050 delivering an 80% reduction in CO_2 emissions. It has also set renewable targets for the year 2020 that relate to consumption, electrical and heat supply. Their ambition is to produce 100% of gross electrical consumption (total generation less net exports) and 11% of total heat demand from renewable resources by this time. In addition, total final energy consumption will be reduced by 12% against 2005-07 consumption (Scottish Government, 2018a).

In 2015, the Scottish Government published a policy document, *"Towards Decarbonising Heat: Maximising the Opportunities for Scotland"*, which outlines its strategic plans for the development of renewable heat (Scottish Government, 2015). The document adopts a holistic and whole-system approach to the supply of heat and follows similar policy documents related to electrical generation, sustainable housing and community energy. Towards Decarbonising Heat addresses the three principal elements of heat supply – consumption, distribution and storage, and, generation – and aims to improve system resilience, lower costs, and decarbonise heat supply.

The overall strategy of the document centres on: lowering the national heat demand through efficiency measures; identifying future potential and the mechanisms required to realise it; promoting new technologies and feasibility studies into their exploitation; and, developing the role of communal and district heat networks. The Government has declared energy efficiency to be a national infrastructure priority with Scotland's Energy Efficiency Programme. Its holistic approach recognises the interaction between efficiency measures and lowered heat demand. This may encourage the use of low-temperature heating which could produce a consequential impact on the feasibility of new, and more efficient, supply technologies.

The statement, emphasises the development of DHN and takes as its headline policy targets to provide 1.5TWh of heat to 40,000 homes connected to such networks by 2020. This follows the Heat Policy Scenario Model which proposed that 8TWh of low-carbon heat could be provided by district heating networks by 2050. It views these systems as a means of providing affordable and resilient heat from low-carbon and waste heat sources. A further aim is to develop community heat systems for which DHNs are ideally suited.

1.1.5. The Finances of Renewable Heat

In combination with the 2015 policy statement, the Scottish government has established multiple loan and grant schemes to encourage the immediate development of low-carbon heat installations. This comes on top of UK Government subsidy schemes to improve the operating finances of low-carbon technologies. Several of the key schemes are discussed in this section.

Renewable Heat Incentive

This is a subsidy scheme run by the UK government and available to domestic and non-domestic installations. It provides payments over seven years for certain types of renewable heat generation based on the amount of renewable heat generated by the system. The subsidy rate varies based on technology and capacity and not all low-carbon technologies are eligible. Those that are include, ground-source heat pumps (GSHP) which includes WSHPs, air-to-water HPs, biomass boilers and solar thermal panels. There are further eligibility requirements that must also be satisfied. Current tariffs for these technologies are provided in Table 1.1.

Table 1.1: Non-domestic RHI tariffs (Ofgem, 2018)

		ASHP	Biomass	W/GSHP	Solar Thermal	Deep Geothermal
Tariff (p/kWh)	Tier 1	2.69	3.05	9.36	10.75	5.38
	Tier 2	-	2.14	2.79	-	-

District Heating Loan

This is a Scottish Government loan, administered by the Energy Savings Trust, of up to £1m. It is available to organisations developing low-carbon district heating networks and can cover the full cost of a scheme. Its intention is to help support the costs of development and the initially high expense associated with the installation of the network infrastructure. These costs have meant that obtaining private finance can be a significant barrier to their development. An appraisal of 22 networks awarded the loan found that 11 would likely not have gone ahead without it (EST, 2015).

Low Carbon Infrastructure Transition Programme

This collaborative Scottish Government programme provides a range of services including advice, support and financing to low-carbon developmental projects. It aims to stimulate inward investment from private finance to support low-carbon technologies. Although broader than the provision of capital, this programme contains several funding streams for specific project types including WSHPs, geothermal energy and local or rural based projects. DHNs in Glenrothes, Glasgow, Clydebank, Dundee and Stirling have won funding from this programme. The heat sources for these schemes include biogas CHP from anaerobic digestion, biomass CHP, river-source and ground source heat pumps, solar thermal and sewer waste-water heat recovery (Scottish Government, 2018c).

1.2 District Heating Networks

1.2.1. Overview

District heating is a means of supplying heat for space heating and/or cooling and/or domestic hot water production to multiple buildings from a small number of heat generation sites. In many cases, systems utilise waste heat as an energy source. The full network comprises generation, distribution and consumption sub-systems, which are common elements to all DHNs. Heat supply occurs at centralised locations termed Energy Centres (EC). Heat is moved and directed, via a heat carrier medium, through pipes and hydraulic equipment to end users. These pipes are generally buried and heavily insulated to minimise heat loss during distribution. After distribution, the heat is utilised by the end user in conventional domestic plant systems. These fundamental components and basic layout of a DHN are presented in Figure 1.6.

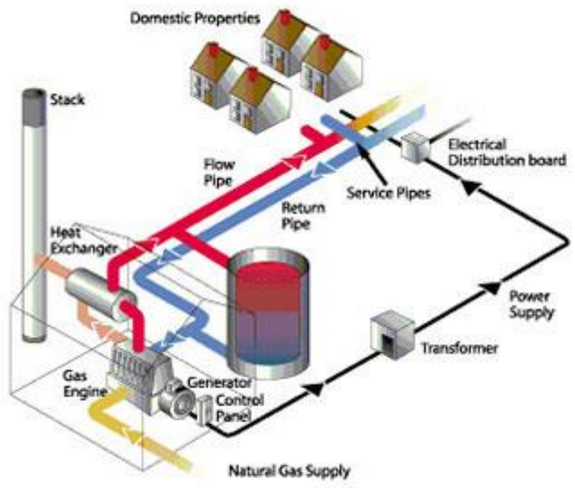


Figure 1.6: Schematic of a CHP district heating network

This broad definition of a DHN encompasses myriad system types. Classification of systems into groupings with similar features aids investigating their operation and performance. Central differentiating characteristics include (Lake et al., 2017):

- **Heat Source.** Heat may be added to the network through any heat generating or transforming technology. The principal classes of heat sources are: fossil fuel and other combustibles, CHP plants, HP, waste heat and solar thermal. DHNs may include several of these supply technologies.

- **Heat Carrier.** The fluid used to transport heat from source to use. In most current systems this is pressurised water but can be steam or air.

- **Heat Type.** Some networks are designed to provide heating (for space heating and/or DHW) or cooling or both functions to users. The heating type is determined by the heat requirements of the area served and impacts heavily on system design.

A central appeal of district heating is the improved efficiency and security that a small number of production centres may have over many distributed supply units (Schmidt et al., 2017). An associated penalty is that attendant losses in distribution are introduced which are not present in building-sited generation.

The installation of the distribution pipework imposes a further capital expense absent from other heating systems. However, the centralised nature of DHN permits the utilisation of site specific resources that are would not be exploitable on an individual basis, especially those which incur a large capital cost.

1.2.2. Historical Development

The past-development of district heating systems is generally accepted to have occurred in three separate “generations”. These generations relate to systems commissioned in temporally distinct periods when different approaches were taken to their design. Each generation was a response to changes in societies use of, and approach to, energy.

First generation systems began in the late 19th century at a time of significant industrialisation. These systems commonly used waste heat from heavy industries and provided heating to high density, residential areas. The heat carrier used was pressurised steam at temperatures of over 100°C. Their adoption sought to remove pressurised boiler equipment from within residences to reduce the risk of steam explosions. However, the distribution networks were susceptible to these failures and their high operating temperatures led to high thermal losses (Lake et al., 2017).

The second generation lasted from the 1930s to the mid-1980s and was characterised by two changes. First, the heat carrier changed from pressurised steam to pressurised hot water in response to steam's safety issues. Secondly, with the electrification of society, the heat resource came increasingly from CHP plants. The adoption of CHP improved the fuel efficiency and financial appeal of the systems. The flow temperatures remained at 100°C or over (Lund et al., 2014).

Third generation technology developed in response to the oil crises of the 1980s and is commonly termed, "Scandinavian District Heating" (Lake et al., 2017). The energy crisis prompted a focus on the energy security and efficiency of systems. Circuit temperatures were lowered to reduce losses and other heat supply technologies were utilised – including biomass, HPs and distributed CHP – to improve resilience and security. Third generation systems introduced pre-fabricated insulated pipework and contemporary heat metering (Werner, 2017).

1.2.3. Design Considerations in Future Systems

There are multiple considerations during the design and commissioning of a district heating system. Some central choices derive from the three classification categories presented previously. Within these, the key requirements are to design a system with minimal cost for the operator and end user while maintaining the ability to meet peak and annual demands on the system (CIBSE, 2014a).

An initial decision is the type of heat to be supplied. Different services require heat at different temperatures and so the circuit supply temperatures are influenced by this. As the heat network serves a large area, the heat requirements of different building types within the community will likely vary (Schmidt, 2017). These differing demands may arise from buildings with different uses (domestic and non-domestic) or from the built form and age of the building. The demand diversity of the area impacts the peak load and, consequently, sizing of the heat generating plant (Nord et al., 2018). If it is deemed that the network must provide heating and cooling, then the configuration of the system may have to incorporate separate pipework for each service.

The delivery of the heat services can be done either directly or indirectly. In the former case, the heat carrier is used directly in the buildings heating system, whereas in the latter a sub-station is used to transfer heat between the network and the end-use building. The hydraulic separation inherent in an indirect network improves system security and resilience. The sub-station, also called a Heat Interface Unit (HIU), must be designed to operate satisfactorily over a range of conditions. The energy forms provided by the network, determine the required sub-systems and their sizing in the HIU. It is generally a location for metering heat usage too. In many contemporary networks separate heat exchangers are used to produce hot water and space heating. A downside of this approach is that supply temperatures in the network need to be raised to facilitate heat transfer (Werner, 2017).

An important consideration is the distribution network layout from EC to end-use. The design significantly affects the operational efficiency and total capital costs of a scheme (Nord et al., 2018). Networks may adopt a branched, looped or ring topology. A downside of the branched network is the extra hydraulic equipment required to ensure acceptable pressures around the network. The users closest to the energy source experience higher pressure, and so higher mass flow and better heat delivery, than those further removed. Ring and looped networks overcome this by establishing equal pipe lengths to and from each building (Schmidt et al., 2017). A key parameter in the feasibility of a proposed network, and the optimisation of the layout, is the linear heat density. This is defined to be the total heat demand per annum per meter of distribution pipe (Nord et al., 2018).

The choice of heat source impacts the likely running costs of the network as well as influencing the optimum operating conditions such as supply and return temperature. It may be influenced by the availability of fuel or energy resources locally. Contemporary best practice is to adopt local renewable resources wherever possible (CIBSE, 2014a). Traditionally, waste heat from industrial processes and heat from CHP systems encouraged the adoption of district heating (Werner, 2017). In certain areas, the viability of CHP is lessening. This comes from renewable electricity depressing electrical spot prices and so alternative sources may be required in the future (Ostergaard and Andersen, 2016). Besides generating technology, the inclusion of thermal storage in the network allows the shifting of load and the avoidance of rapid modulation or cycling of generating plant.

The performance of a district heating network is principally determined by the circuit temperatures and flowrates. These two parameters alongside the thermal properties of the heat carrier determine the transmission and delivery of heat, available services, pumping requirements and losses in the system. Low mass flow rate and high temperatures increase the rate of heat loss during distribution (Schmidt et al, 2017). Flowrate and temperatures must be carefully controlled to ensure adequate heat delivery at minimum cost. For space heating, different building heating systems, such as traditional radiators, low-temperature radiators and underfloor heating, have different temperature requirements. For DHW production, the avoidance of Legionella imposes a minimum temperature of 50°C for instantaneous use and 60°C if the DHW is stored (Elmegaard et al., 2016).

These design considerations are complicated by their interdependence. For example, certain generating technologies operate more efficiently with different supply and return temperatures. Currently, district heating is moving into a fourth generation characterised by lower flow temperatures (at 55°C) and increased renewable heat sources. The challenges and opportunities faced by future heating networks are discussed next.

1.2.4. Low Temperature District Heating and Future Concepts

The contemporary challenges facing the Scottish energy system is its decarbonisation and transformation into a sustainable industry. It is the requirements and consequences of these pressures that will inform the future development of the fourth generation of district heating. The principal aims of 4GDH are efficiency savings achieved through lower losses and the integration of renewable resources, including electrical generators, into integrated smart energy networks (Lund et al., 2014).

Improvements in the thermal envelope of buildings have led to a steady decline in the demand for space heating. With lower heat demand per building, the heat demand density has generally decreased in many areas. While a positive change for the energy use of society it undermines the economic viability of district heating (Averfalk and Werner, 2016). Lower heat demands increase the relative percentage of distribution losses to heat production. This is particularly true in summer. The decrease in heating requirements means that the loading on DHN will become more erratic – with long periods of low demand and distinct periods of high demand (Tereshchenko and Nord, 2018).

Improved thermal performance lowers a building's heating requirements, which can be more feasibly met through low-temperature heating systems. These include low-temperature radiators and underfloor heating, operating on temperature differentials of approximately 40/25°C and 35/30°C, respectively. It is possible to meet space heating requirements for both renovated and new buildings with underfloor heating, although traditional radiator systems may require higher temperatures in the peak heating season (Schmidt et al., 2017).

An opportunity exists to adopt low-temperature networks while satisfactorily providing for space heating requirements. This consequently lowers distribution losses improving the financial prospects of DHN. Low-temperature networks are generally considered those to have supply temperatures of 50-70°C (Pellegrini and Bianchini, 2018). Pipework costs can also reduce with low temperatures through the replacement of steel with plastic piping and the lessening of insulation requirements.

Furthermore, reduced circuit temperatures encourage the integration of renewable heat resources which are often available or operate more efficiently at low temperatures. The coefficient of performance (COP) of heat pumps improves with lower condenser temperatures. A paper looking at the use of booster HPs within a low-temperature district heating network reported a COP of 10 for the central HP during summer. This performance lessens the importance of distribution losses (Ostergaard and Andersen, 2016).

Two central issues exist with lowering temperature, however. First, district heating systems must be designed for all buildings in the serviced area and so circuit temperatures and plant must be compatible with the building presenting the highest temperature requirements (Tereshchenko and Nord, 2018). Since the future building stock will contain a large percentage of older buildings, extensive fabric upgrades and heating plant replacement may be required. Second, the requirement of avoiding Legionella growth in DHW systems necessitates this service to be produced at temperatures of 50°C or higher if it is to be stored.

Legionella prevention is the main barrier to the development of low-temperature district heating. Several approaches exist to overcome the issue. These include chemical, physical and thermal treatments, some of which are still under development (Yang et al., 2016). Currently, the two principal avoidance methods are thermal treatment at over 55°C and by minimising the residency time of hot water (Tereshchenko and Nord, 2018). In practice, for networks with 4GDH temperatures, this can be achieved via high efficiency heat exchangers producing instantaneous DHW or through thermal stores connected to the network side of the building sub-station (Schmidt et al., 2017).

Future networks may surpass 4GDH temperature aims and become ultra-low temperature heating (ULTDH) networks. These would have flow temperatures below 50°C and return temperatures limited by ambient conditions (Pellegrini and Bianchini, 2018). In such systems, although distribution losses are reduced further, additional plant for auxiliary heating of DHW is necessary. The principal ways of achieving this are through direct electrical heating or booster HPs. Due to the higher COP of HPs over electrical heating, they are the predominant suggestion in literature (Ommen et al., 2017; Ostergaard and Andersen, 2016; Elmegaard et al., 2016). There are multiple system configurations using booster HPs but in modelling exercises, it is found that the savings made in reduced distribution losses do not offset the increased capital and operational costs of the auxiliary systems.

Other changes are likely to occur in future district heating networks. To overcome the issue of DHW production in low temperature networks, it has been proposed to decouple this service from space heating (Elmegaard et al., 2016). An alternative approach is to develop a temperature cascade system, where the return stream of a high temperature network acts as the supply stream of a lower-temperature network (Averfalk and Werner, 2016). The nature of the district heating network will evolve too as consumers become prosumers with small-scale, building-located heat generators. This move will require a paradigm shift in the control of district heating and the legislative context it operates in (Terenshchenko and Nord, 2018).

1.3 Modelling District Heating Networks

1.3.1. The Physics of District Heating Networks

District heating networks are complex thermo-mechanical systems. The transport of heat from generation to consumption sites involves transient thermodynamic interactions and mechanical behaviour. Therefore, modelling the behaviour of such systems is a highly involved task. The network’s full behaviour is encompassed in the fundamental conservation equations of thermo-fluid dynamics, provided below (Cengal et al., 2012).

Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \hat{v}) = 0 \qquad \text{Equation 1.}$$

Conservation of x-momentum

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho \hat{v} \cdot u) - \nabla \cdot \mu \cdot \nabla u = -\frac{\partial p}{\partial x} \qquad \text{Equation 2.}$$

Conservation of y-momentum

$$\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho \hat{v} \cdot v) - \nabla \cdot \mu \cdot \nabla v = -\frac{\partial p}{\partial y} \qquad \text{Equation 3.}$$

Conservation of z-momentum

$$\frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho \hat{v} \cdot w) - \nabla \cdot \mu \cdot \nabla w = -\frac{\partial p}{\partial z} \qquad \text{Equation 4.}$$

Conservation of Energy

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho \hat{v} \cdot e) - \nabla \cdot k \cdot \nabla e = \rho S + \varphi \qquad \text{Equation 5.}$$

The simultaneous solution of these coupled partial differential equations across a network at a point in time, defines the time-evolving behaviour of the system at that moment. However, the solution of these full conservation equations is computationally intensive and arguably unnecessary for the purposes of district heating network.

Several assumptions and simplifications are commonly applied to these equations for the efficient modelling of district heating networks. First, it is assumed that the dynamic mechanical behaviour of the fluid can be ignored. This involves adopting a quasi-dynamic approach where the thermal behaviour is modelled dynamically, while the fluid dynamics are modelled in a steady manner (Gabrielaitiene et al., 2007). This is deemed acceptable because of the relative propagation speeds of the two phenomena in water. Pressure changes, which principally determine the flow dynamics, propagate at speeds orders of magnitude greater than the transport of the mass itself. The thermodynamics of the fluid, on the other hand, is linked to the mass flow and the heat transfer processes occurring at its boundaries (Stevanovic et al., 2009).

A second common assumption is the dimensional reduction of the conservation equations. Heat transfer from the distribution water through the pipe wall is assumed to only occur in the radial direction – with no temperature gradients along the length of the pipe. Likewise, the fluid flow is assumed to be 1-dimensional along the axis of the pipe. A further simplification is modelling the fluid motion as 'plug flow' which assumes no viscous effects occur between adjacent layers of fluid (Zheng et al., 2017).

Modelling Approaches

The equations and simplifications of the previous section are utilised in the construction of detailed, physical models of district heating networks. These models operate according to the known physics of the system and not from statistical or monitored data from real systems. This latter approach is termed a 'black box' model (Talebi et al. 2016).

In much literature, research is concerned with the transport dynamics of district heating networks. The aims of these works are to understand and evaluate the propagation of temporary temperature occurrences around the network with consideration of heat losses from the pipework ((Stevanovic et al., 2009), (Zheng et al, 2017), (Jie et al., 2012)). This approach relies on following the temperature disturbance around the network as it travels with the flowrate in time. However, physical models allow the full state of the system to be determined and so many other performance investigations are possible.

A common implementation of physical models uses a node-based topology. This establishes multiple evaluation nodes at key points of the network. Components are included which link relevant nodes together (Yildirim, 2002). In this approach the components contain the physical definition of the process they represent. These approaches include the nodal network and lumped parameter methods.

1.3.2. Review of Simulation Software

There are numerous different implementations of physical district heating models in literature. In (Talebi et al, 2016) 15 studies are presented which were published over a three-year period. Each of these utilised the above principles of physical modelling within different implementations. These will not be reviewed here, and instead, a couple of available commercial software packages will be discussed.

EnergyPro

EnergyPro is primarily a technical and financial feasibility software for heating projects. It can incorporate heating, cooling and electrical networks in a model and so is particularly well suited for CHP and trigeneration schemes. Elementary components are provided for common plant in such systems and the user supplies data regarding capacity, performance and losses (EnergyPro, 2018).

The user also supplies electrical and fuel tariffs, and load profiles from which the software optimises its annual performance to achieve adequate supply at minimal cost. This optimisation algorithm, assumes perfect predictive knowledge such that all demands are known in advance by the software. The outputs from a simulation are financial and economic analyses alongside performance alongside operational schedules.

TRNSYS

TRNSYS is a transient simulation software developed for the modelling of thermal systems. It is built around the use of Proformas which underpin every available component. These have an input-output relation where the physical behaviour of the component is coded in the mathematics of the Proforma. The programme was initially developed for the appraisal of solar thermal systems, but its capacity has grown dramatically since then (TRNSYS, 2004).

It is possible to include buildings in the simulator which generate demands on the system. The TESS library of components increases the breadth of studies that can be conducted. Besides physical components, equations and controllers are available to introduce control routines to the model. There are additional utility components such as weather generators, ground temperature profilers, and electrical components. A further strength of TRNSYS is in the ability of the user to specify new components through the development of new Proformas – providing extra flexibility in modelling.

These features allow many systems to be modelled and make the software particularly appropriate for the detailed modelled of district heating systems. In this project, TRNSYS was selected for the simulation of district heating networks.

1.4 Chapter summary

This chapter has established the need to overhaul Scottish heat supply by exploiting the varied and plentiful renewable resource it possesses. It presented the relatively low deployment of renewable heat technologies and argued that large scale district heating systems are an important means of changing this.

It also introduced the basics of district heating systems and their historical development. At present a conceptual transformation is occurring, ushering in the 4th generation of district heating – typified by lower circuit temperatures and the integration of renewable heat technologies. The benefits of this move were established alongside some pressing issues with low flow temperatures.

Modelling methods for such systems were then discussed. This involved establishing the fundamental physics of such systems and the methods used to model them in contemporary research. A short review of available software was then provided, including the software used in this project: TRNSYS.

From this section, the basis has been laid for the investigation of low and ultra-low temperature district heating networks for deployment at HALO Kilmarnock. In the next chapter, the HALO development is introduced alongside assessments of the project's heat demand and available resources.

Chapter 2: Demand and Resources at HALO Kilmarnock

2.1 The HALO Development and Kilmarnock

The HALO development is an urban regeneration project in the Ayrshire town of Kilmarnock. It is located at the site previously occupied by the Johnnie Walker bottling plant near to the town centre. This brownfield site will be the location for an extensive modern development of residential, commercial and recreational spaces and the HALO project seeks to become an archetype for the regeneration of urban post-industrial areas (HALO, 2018). The site is given in Figure 2.1.

Figure 2.1: The HALO Kilmarnock site

2.1.1. Current Plans

At the core of the project are plans for a large ‘Innovation Hub’ which will contain retail space, a restaurant and two floors of open plan office space. The project intends to attract high-tech businesses and start-ups to the Innovation Hub. Through this it aims to develop links with local educational establishments to nurture technological and IT skills in the local population.

Asides the Innovation Hub, plans exist to construct 210 dwellings, 26 ‘Live-Work’ spaces – where occupants can work from a space in their dwelling, religious and leisure centres, and recreational green spaces. To augment their vision, HALO plans to adopt cutting-edge technology wherever possible including the energy provision onsite. It intends to provide heat via a district heating network powered by energy contained in a deep geothermal aquifer 2km under the site (HALO, 2018).

The project will be commissioned over two phases. Although it is proposed that work will begin in 2019, there is currently limited available information regarding the project. Only generic information related to the size, use and number of each building type have been confirmed. This information is presented in Table 2.1 for domestic and non-domestic buildings (VEUL, 2017).

Table 2.1: Building information for HALO

Non-Domestic Buildings

Name	Building Type/Use	Phase	No.	GIA (m^2)
Innovation Hub	Office, Plant Rooms, Retail & Café.	1	1	5064
Live-Work Studios	Residence & Office Space	1	13	88
Live-Work Studios	Residence & Office Space	2	13	88
Provisional Offices	Offices	2	1	3000
Wave/Surf Centre	Leisure Centre	2	1	2222
Religious Facility	Religious space	2	1	400

Domestic Buildings

Name	Building Type/Use	Phase	No.	GIA (m^2)
Duplex	Semi-detached	1	44	84
Duplex	Semi-detached	2	46	84
Terrace	Terrace	1	26	89
Terrace	Terrace	2	46	89
Flat	Flat	2	46	58

The domestic building floorspaces were taken from the Scottish Housing Condition Survey for typical dwellings of these type (Scottish Government, 2018b). The total floorspace of 16636 m^2 was in close agreement with the reported value of 16800 m^2.

2.1.2. Kilmarnock Town

Kilmarnock is a town located in the southwest of Scotland and is the administrative centre for East Ayrshire Council. It is located approximately 11km from the coast. The population of the town is roughly 45,000. An indication of the demography of Kilmarnock is provided by the East Ayrshire results of the Scottish Household Survey. These indicate that the area has a similar demography to the rest of Scotland with respect to age, gender, ethnicity, religion and marital status. The net income and employment status within households are only slightly lower than the average Scottish breakdown (Scottish Government, 2016).

A significant proportion of East Ayrshire’s population live in deprived areas according to the Scottish Index of Multiple Deprivation (SIMD). According to the 2016 Survey, 38% and 26% of the population belong to the most, and second most, deprived quintiles, respectively. This is reflected in how people manage financially where, across all income brackets, a higher percentage than the rest of Scotland felt they had not coped well financially the previous year. This comprised 12% of the overall population (Scottish Government, 2016).

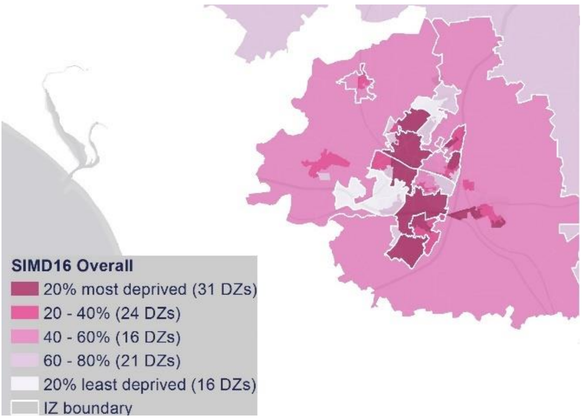


Figure 2.2: Kilmarnock areas by SIMD quintile

A consequence of this deprivation and a symptom of the financial struggles of a portion of the population is that fuel poverty is an issue in the area. This is defined to be when over 10% of household income is spent of fuel costs. According to the Scottish House Condition Survey, East Ayrshire had the 9th highest level of fuel poverty out of 32 local authority areas (Scottish Government, 2018b). The percentage of households in fuel poverty across the local authority area was 38%.

Of the eight councils with higher levels of fuel poverty, all were rural areas and included the five remotest areas in Scotland (Shetland, Orkney, Argyll and Bute, Highland and Na h-Eileanan Siar) where gas-grid connections are lowest. These five areas also had between 3-5 times the Scottish average of F and G rated dwellings in terms of energy efficiency according to the Standard Assessment Procedure (Scottish Government, 2018b).

2.1.3. Energy Performance of Kilmarnock Buildings

The Scottish House Condition Survey provides a review of the quality, composition and energy usage of dwellings in Scotland. The data it contains provides a national picture of Scotland with some results related to local authority areas. As the present work focussed on a specific area, the benchmark energy performance of East Ayrshire buildings was determined by analysing the EPCs available for the area. All domestic EPCs were extracted and those whose postcodes did not relate to Kilmarnock town were filtered out (Scottish Government, 2018e).

The Kilmarnock sample contained 7700 EPC records over the period of October 2012 to March 2017. The records included those for new and existing properties. The housing stock was composed of 33% flats, 22% terraces, 28% semi-detached, 15% detached and 2% maisonettes. The SAP evaluations were used for two purposes. First, to identify the overall energy performance of existing buildings in Kilmarnock and, secondly, to identify the likely energy use of new builds in the town.

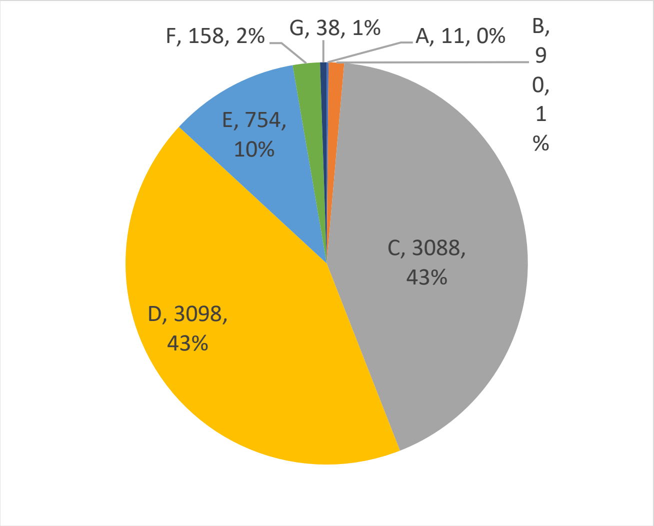


Figure 2.3: Existing buildings EER by band

The breakdown of Energy Efficiency Rating (EER) by band across the existing housing stock is presented in Figure 2.3. Most properties are in the C or D bands and the average EER rating was 65. These values are broadly in line with the Scottish average. In terms of energy use, the average requirements for space heating and domestic hot water were approximately 10,500 kWh/a and 2,300 kWh/a, respectively. Assuming the primary heating systems were gas-boilers with an efficiency of 90%, the average gas consumption for the area was 14,200 kWh/a – 6% higher than the Scottish average.

These demands, normalised to the floor area, were 121 kWh/m^2a and 29 kWh/m^2a for space heating and domestic hot water, respectively.

New-builds would be expected to have significantly better energy efficiency and lower energy use than existing buildings. Of the sample, 485 were new dwellings composed of 56% detached, 22% semi-detached and 11% flats or terraces. Of this sample only 2 belonged to the C EER band while all others had a B banding. The space heating demand of new-builds is not reported in the data, but domestic hot water demand is. For this service the demand estimates ranged from 1450 – 2400 kWh/a with a mean value of 2000 kWh/a. This demand, normalised to floor area, was 20±8 kWh/m^2a.

For space heating requirements, it was necessary to rely on the requirements of ‘existing’ buildings. Since almost all new-builds were in the B-band, it was assumed that this is standard practice for all new-builds in the area. The sample was limited to these existing dwellings. Furthermore, the installation of building renewables improved the EER of a dwelling without necessarily enhancing its thermal performance. Thus, to accurately represent the space heating requirements of new dwellings with good thermal performance, the buildings with integrated renewables were removed from the sample. Using this sample of 46 buildings, 78% of which were flats, the average space heating requirement was found to be 5500 kWh/a. Normalised to floor area, the heating requirements ranged from 15 – 68 kWh/m^2a with a mean value of 39 kWh/m^2a. It was assumed that the space heating demands at HALO will reside within this range.

The total heat demand for Kilmarnock according to the Scotland Heat Map was 515 GWh/a (Scottish Government, 2018d). The distribution across the town is given in Figure 2.4. Taking an average household occupancy of 2.35 (derived from statistics in Scottish Government, 2016) the number of dwellings in Kilmarnock is approximately 19,000. Using the previously determined average heat demand per property of 12.8 MWh/a, the total demand for domestic heat in the area is 243 GWh/a. This equals 47% of the heat demand of the town which is in good agreement with the national split (43%) between domestic and non-domestic heat requirements reported earlier.

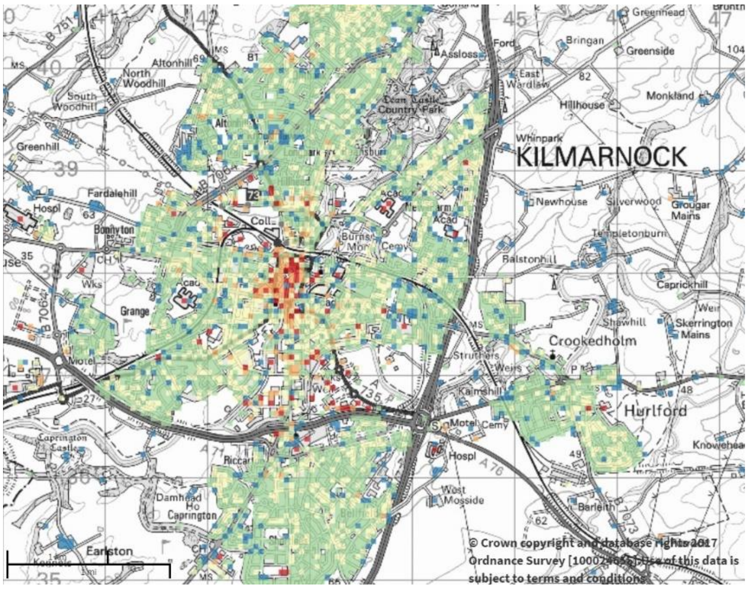


Figure 2.4: Heat density in Kilmarnock

2.2 Demand Assessment

2.2.1. Benchmark Demands

The design of a DHN requires an assessment of the likely heat demand in annual and seasonal, total and peak terms. This allows the supply and distribution plant to be appropriately selected and sized. Best practice involves modelling the heated buildings under various weather and occupancy patterns. For the HALO project, detailed plans were not available and so a benchmarking approach was adopted.

A variety of benchmarks from the Chartered Institute of Building Engineers (CIBSE) *Energy Benchmarks* are provided in Table 2.2 (CIBSE, 2008). These were the most appropriate values for the building types at HALO Kilmarnock.

Table 2.2: CIBSE fossil fuel consumption benchmarks

HALO Building	CIBSE Class	Typical Fossil fuel consumption (kWh/m^{2}a)
Residential	General accommodation	300
	Long-term residential	420
Live-Work Studios	Long-term residential	420
Innovation Hub & Speculative Offices	General Office	120
Wave-Surf Centre	Swimming pool	1130
Religious Centre	Public Building with light usage	105

These benchmarks are for fossil fuel consumption and so cover space heating, domestic hot water production, cooking and other miscellaneous activities which burn fossil fuels. The demands of space heating and domestic hot water dominate consumption and so these values were taken to be the annual energy use for these activities.

A further set of benchmarks were provided by Vital Energi Utilities Limited (VEUL) who conducted a preliminary study into the sizing of a district heating network for HALO Kilmarnock. The normalised heat demands for both space heating and domestic hot water from their *Stage 3 Report* are provided in Table 2.3 (VEUL, 2017).

Table 2.3: VEUL annual demand benchmarks

Building type	Space Heating (kWh/m^2 p.a.)	DHW (kWh/m^2 p.a.)
Innovation Hub	91	9
Speculative Offices	128	9
Live-Work Studios	91	9
Wave-Surf	91	9
Religious Facility	157	7
2-bed dwellings (All)	29	1000 kWh/unit p.a.
3-bed dwellings (All)	29	1250 kWh/unit p.a.

The CIBSE benchmarks for residential fossil fuel demand are significantly higher than both the VEUL benchmarks and the demands determined from the previous analysis of EPCs in the Kilmarnock area, which were in greater agreement. For this reason, it was decided to use VEUL's benchmarks for the demand analysis. The CIBSE benchmarks were devised to apply to multiple buildings in a class with different thermal standards and ages. It was therefore thought more appropriate to use VEUL's benchmarks for each building which were the results of a site-specific study.

The heat demand analysis was conducted using the benchmarks contained in Table 2.3 and the building details from Table 2.1. The results are presented in Table 2.4 in terms of annual heat demands. This includes the demand breakdown for each building type across both phases of the HALO development.

Table 2.4: Breakdown of annual heat demand across HALO development

Building	Per Property Annual demands		Total Annual Demand	
	Space Heat (kWh)	DHW (kWh)	Phase 1 (MWh)	Phase 2 (MWh)
Duplex (3-bed)	2436	1250	162.2	169.6
Terrace	2581	1000	93.1	164.7
Flat	1682	1000		123.4
Innovation Hub	460,824	45,576	506.4	
Live-Work	8008	792	114.4	114.4
Speculative Offices	384,000	27,000		411
Wave-Surf Centre	202,202	19,998		222.2
Religious Facility	62,800	2800		65.6

Totals (MWh)	876	1271
	2147	

2.2.2. Heat Demand Profiling

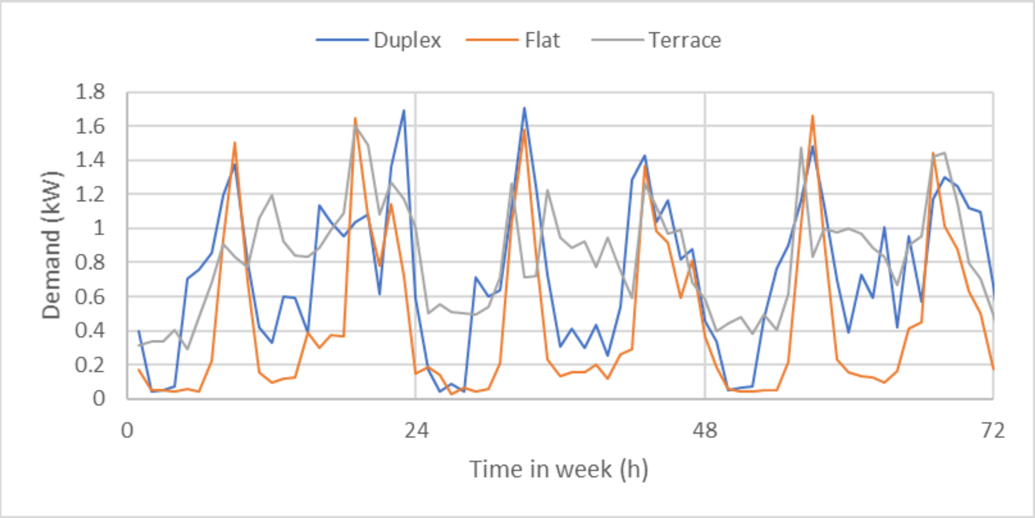
To investigate annual variations and for the purposes of modelling it was necessary to produce temporal profiles of the heat demand. Monitored data from similar buildings were used to produce representative hourly profiles. The dataset used, from the work of (McGhee, 2012), contained a mixture of dwelling types and public buildings. Separate profiles were formed for each building type at HALO.

Domestic Buildings

The domestic building data came from the Milton Keynes Energy Park and were collected from 1989-1991. Although standards have improved, these buildings had high thermal performance corresponding to SAP EERs of 75-90 (UKERC, 2018). The profiles were therefore representative of possible demands at HALO. The data collected related to gas consumption and so represents a combination of space heating and DHW demands.

The profiles were scaled to the total predicted consumption outlined in Section 2.2.1. A degree of diversity was inherent in the readings and further diversity was introduced through the averaging of profiles across several dwellings of the same type. Profiles over several winter and summer days are presented in Figure 2.5(a) and (b), respectively.

(a) Winter week



(b) Summer week

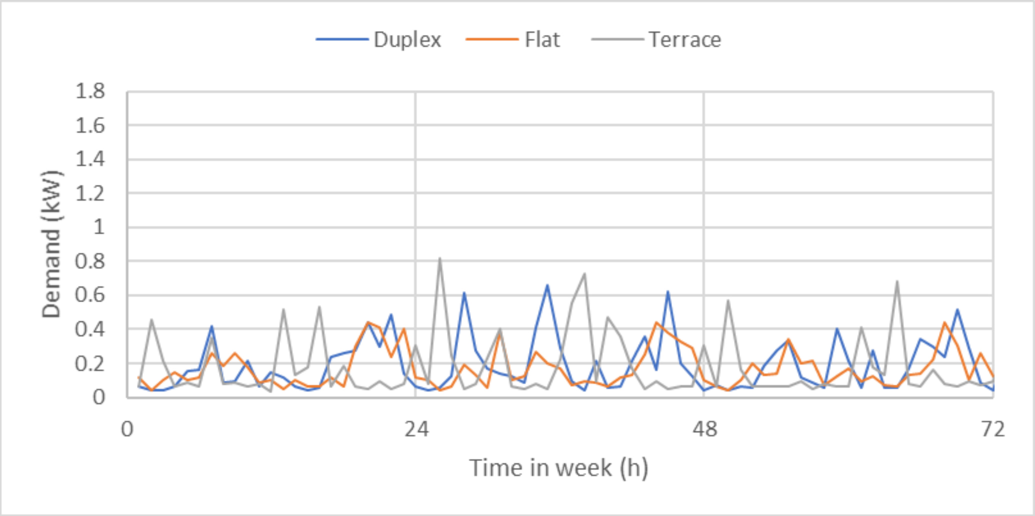


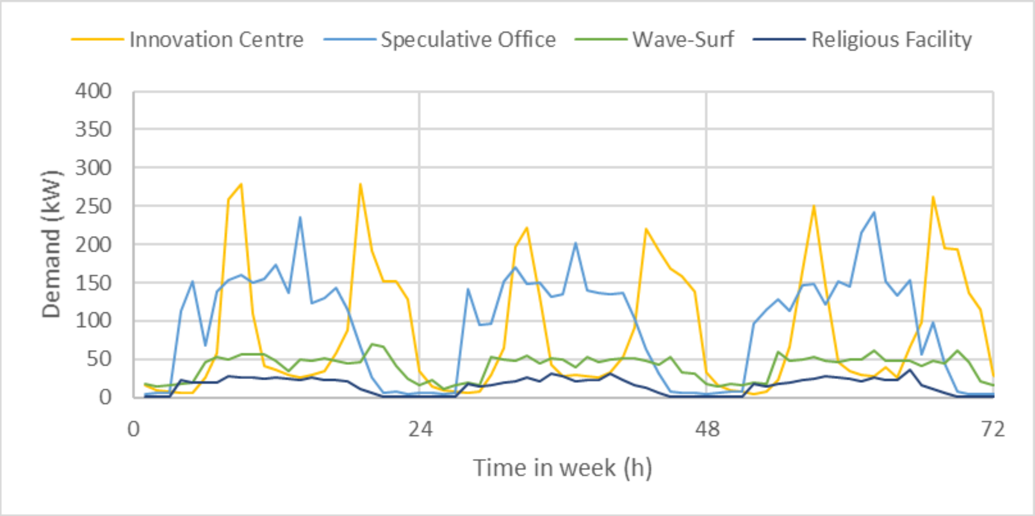
Figure 2.5: Domestic demand profiles by dwelling type

Non-Domestic Buildings

The non-domestic building data were monitored at various public buildings across the UK. The dataset contained buildings with different uses including offices, schools, leisure centres, libraries, universities, care homes, museums and community centres. The most appropriate buildings type for each non-domestic building at HALO were identified.

This assessment was based on the author's judgement with regards to the likely occupancy and use patterns alongside consideration of the age of the monitored building and its floorspace. It was decided to base: the Innovation Hub and speculative offices on separate Scottish council buildings; the Wave-Centre on a Scottish leisure centre; and, the religious facility on a Scottish library. Profiles for each of these buildings over several winter and summer days are presented in Figure 2.6.

(a) Winter week



(b) Summer week

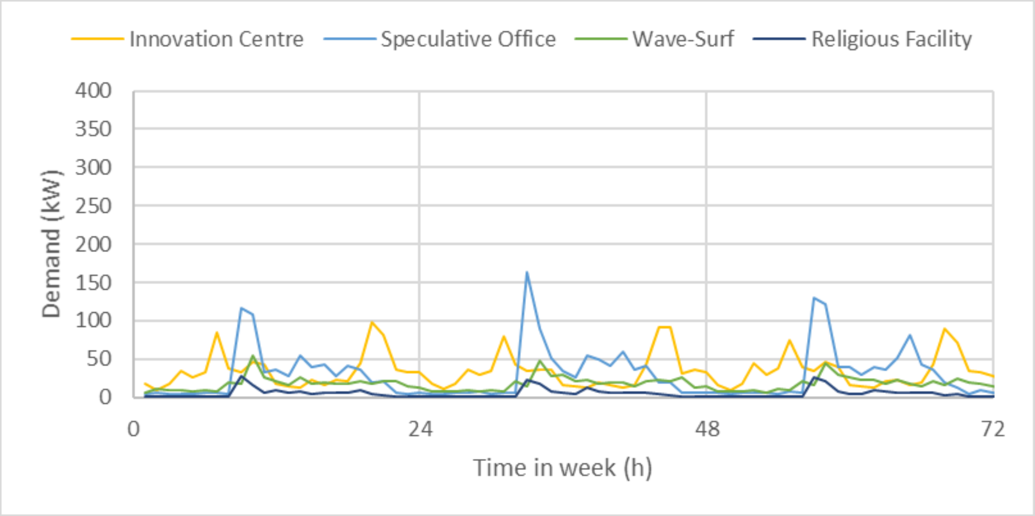


Figure 2.6: Non-domestic demand profiles

Although these profiles do not relate directly to the buildings at HALO, they allow representative daily and seasonal variations in demand to be explored. Future work should simulate each building type under different occupancy and use patterns to determine detailed heating and cooling requirements.

2.3 Resource Appraisal

With demand profiles for the buildings at HALO determined, the local renewable resources need to be identified and quantified. In this section, each resource is assessed before being compared to the seasonal demands in Section 3.1. For each assessment, specific details are presented alongside the methodology adopted and the results. Conservative assumptions are used to provide a lower bound for the likely resource.

2.3.1. Resources in Kilmarnock Area

The Scotland Heat Map was used to identify all renewable installations and renewable heat resources in Kilmarnock area. No records were present for Kilmarnock town itself as shown in Figure 2.7. The heat resources in Irvine are too distant to be exploited by HALO. In the surrounding area, there are multiple operational wind farms. These indicate the potential for wind turbine generators at the site. The potential also exists to provide a grid service by scheduling electrically powered heat devices to absorb local excess renewable generation. These options, however, are out with the scope of the current project.

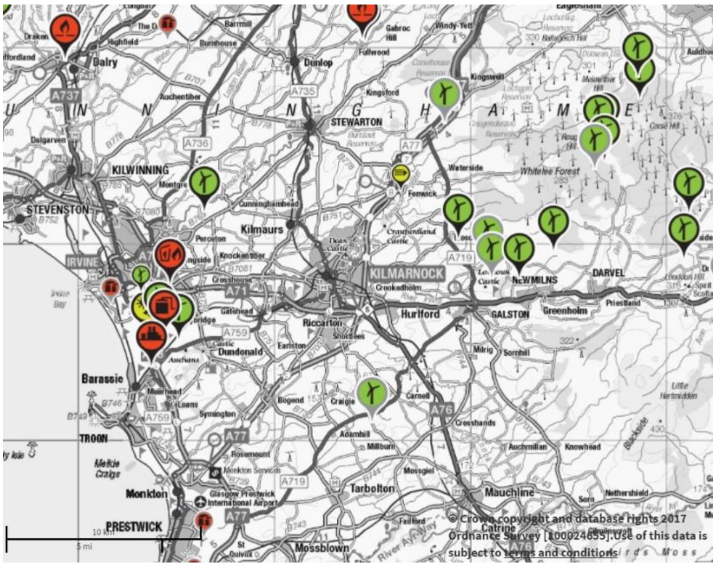


Figure 2.7: Renewable resources and installations in Kilmarnock area

Kilmarnock’s climate is responsible for many naturally occurring heat resources. Weather data over 25 years was retrieved from Prestwick RAES (NCDC, 2018) located approximately 14km from HALO. Monthly solar radiation values were taken from a Wood Group resource assessment for the site (Wood Group, 2018). Average monthly climate values are provided in Table 2.5. Hourly profiles were produced from these monthly values using the TRNSYS weather generator module.

Table 2.5: Kilmarnock monthly weather averages

Month	Dry-bulb Temperature	Global Horizontal Radiation	Windspeed	Relative Humidity
	(°C)	(kWh/m^2)	(m/s)	(%)
Jan	4.4	16.0	11.0	86%
Feb	4.3	32.3	12.5	85%
Mar	5.2	67.7	11.5	82%
Apr	6.8	107.4	8.8	78%
May	9.6	145.6	9.0	76%
Jun	11.9	143.8	8.3	79%
Jul	13.8	140.2	9.1	80%
Aug	13.7	114.2	7.9	81%
Sep	11.8	75.0	8.5	81%
Oct	9.1	43.4	9.6	83%
Nov	6.5	20.2	9.8	84%
Dec	4.3	11.9	11.8	87%

The HALO project scoped-out the use of biofuels and CHP generating plant due to their local air emissions. These potential resources were therefore not assessed as part of this project.

2.3.2. Ambient Resources

Although ASHP and GSHPs are well established and widely deployed technologies the available resource for each will not be determined. The ground resource is highly influenced by ground water flows, which convey heat through the ground. Without an understanding of this site characteristic, it is impossible to accurately assess the resource. As this information and data were not available the resource was scoped out.

Similarly, it was thought that the air resource would be insufficient in the peak heating season (when temperatures are on average 4.3°C) without the installation of substantial excess-capacity. As it would be impractical to meet baseload with this technology, the resources used by other HP types were preferential assessed.

Solar Thermal Assessment

The monthly resource available for solar thermal panels was previously provided in the *Global Horizontal Radiation* column of Table 2.5. These monthly values were used in the TRNSYS weather generator to produce a temporal supply profile.

2.3.3. Waterways

Two rivers flow through Kilmarnock: the Irvine and Kilmarnock Water. Kilmarnock Water passes within 500m of the proposed EC, while the River Irvine passes 1.4km to the south of HALO (Google Earth, 2018). The routes are presented in Figure 2.8. The Irvine is the greater of the rivers with a catchment of 218 km^2 compared to 74 km^2 for Kilmarnock Water which is a tributary (SEPA, 2018b). Due to the small size of Kilmarnock water and a lack of monitored flowrate data, it was scoped out as a potential source. Although the River Irvine is considerably further from the HALO site, its potential was assessed instead.

Figure 2.8: Location of waterways in Kilmarnock

Waterway Assessment: Method

A control volume analysis was used according to Equation 6.

$$\dot{Q} = \dot{m} C_p \Delta T$$

Equation 6.

Where $\dot{m}$ is the mass flowrate, C_p is the specific heat capacity of water (4.18 kJ/kgK) and ΔT is the permitted drop of the abstracted water. Daily mean flowrate data covering the years 1987-2015 were retrieved for the River Irvine (NRFA, 2018). This long period increases confidence that the data contains all possible flowrates. The temperature of the river is not monitored. In place the assumption was made that the water temperature equalled the mean monthly air temperature[ii].

There are no explicit guidelines from the Scottish Environment Protection Agency regarding permitted abstraction volumes or the temperature to which abstracted water can be cooled. The Controlled Activity Regulations (CAR) are concerned with the daily amount of water abstracted for defining thresholds in the consenting process and

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[ii] This assumption comes from the Standard Assessment Procedure for surface water heat pumps (BRE, 2017).

determining subsistence charges (SEPA, 2018a). It was assumed the abstracted water could be lowered by $\Delta T_{max} = 5°C$. Similarly, although no SEPA guidance was available, it was assumed that a maximum of 10% of the total river flow could be abstracted and that the system would have a maximum intake of $\dot{m}_{max} = 200$ kg/s.

The assessment was carried out for every day that the flowrate and weather data coincided. This comprised the following calculation steps:

1. The permitted abstraction flowrate i.e. $\min\{0.1 \cdot \dot{m}_r \,, \dot{m}_{max}\}$
2. The practicable temperature drop i.e. $\min\{\Delta T_{max} \,, (T_r - T_{freeze})\}$
3. The average daily resource according to Equation 6.

Although conservative estimates were used, the abstracted flowrate and temperature drop were both maximised to give a maximum average heating power.

Waterway Assessment: Results

The 23 years of coincident data were arranged to provide the average and minimum heating power in the river for each day of the year across the data period. These profiles are provided in Figure 2.9.

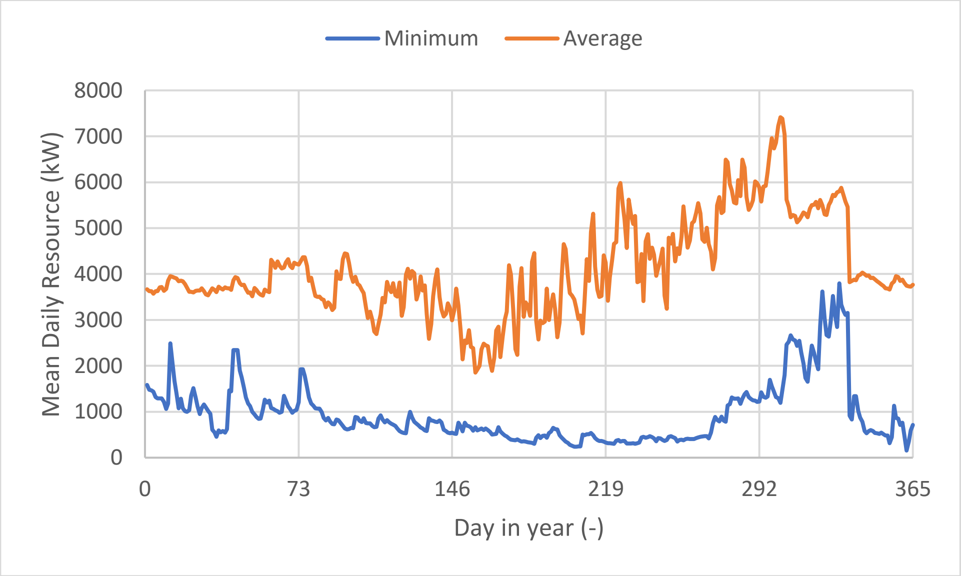

Figure 2.9: Exploitable resource of the River Irvine

2.3.4. Waste Heat

A review of industry in the area did not reveal any substantial waste heat resources. As in any urban area, however, heat in the sewerage system is a substantial and largely untapped resource. New utilities will be required for the HALO development and this offers the opportunity to install heat recovery systems. Extracting excessive heat from sewers can impact wastewater treatment processes. The closest treatment plant to HALO is approximately 10km to the west (Defra, 2012). This distance provides time for the temperature to recover.

Heat in the sewer network arises from waste water streams. The resource is therefore heavily dependent on the occupancy of, and activities within, the connected occupied buildings. Heat can be recovered in a passive way with heat exchangers built into the sewer pipework or can be actively removed with the incorporation of a heat pump. It is this later situation that is assessed here. Warm water streams arise from showering, bathing, hand washing, dish-washing and the use of certain appliances such as clothes and dish-washers (Bertrand et al., 2017a). The resource was assessed for the whole site.

Wastewater Assessment: Data, Assumptions and Method

Data regarding the frequency and duration of each activity, alongside its waste water temperature and flowrate, are detailed in Table 2.6. Occupancies of 2.35 per dwelling and daily occupancies of 1000 across the non-domestic buildings was further assumed.

Table 2.6: Waste stream data and assumptions (Bertrand et al., 2017b)

Activity	Flowrate	Drain Temp.	Daily Frequency	Duration	Associated User
	(kg/s)	(°C)	(1/day)	(mins)	(-)
Hand-washing	0.08	40	3.15	0.25	Individual
Showering	0.08	37.5	0.7	8.5	Individual
Bathing	0.2	39	0.044	10	Individual
Dish washing (by hand)	0.2	32	0.9	3.25	Household
Dish washer (appliance)	0.07	54	0.3	3	Household
Washing machine	0.17	37	0.45	1	Household

The daily resource was found by summing the contribution from each waste water stream according to Equation 7.

$$Q = \sum_{i}^{n} \dot{m}_i \cdot c_{p,i} \cdot \left(T_{dt,i} - T_{amb}\right) \cdot f_i \cdot n_i + \sum_{j}^{m} \dot{m}_j \cdot c_{p,j} \cdot \left(T_{dt,j} - T_{amb}\right) \cdot f_j \cdot n_j$$

Equation 7.

For n streams associated with individuals and m streams associated with buildings. Here, $\dot{m}_{i,j}$ and $T_{dt,i,j}$ are the waste stream's flowrate and temperature respectively; $f_{i,j}$ are the daily frequencies; $n_{i,j}$ are the number of occupants and buildings respectively and c_p is the specific heat capacity of the water.

Wastewater Assessment: Data, Assumptions and Method

The estimated sewer-heat resource, using Equation 7 with the data in Table 2.6., was found to be approximately 1.1MWh/day. The energy demand for DHW using the VEUL benchmark values in Table 2.3 was calculated to be 0.95MWh/day. As appliance waste streams are not considered in the latter, these figures are in good agreement.

Although the resource will vary in time, both annually and daily, only the average recovery power was considered here. CIBSE benchmark for waste water generation are 200l/day for a resident and 100l/day for an office worker (CIBSE, 2014b). The average sewer flowrate was then 2.86 kg/s and its average temperature was roughly 4°C above ambient.

As with SEPA, heat extraction limits set by Scottish Water are not publicly available. Scottish Water Horizons, use the assumption that a 5°C drop can occur across a sewer waste water heat pump (SR, 2018). As these two temperatures are close, the more conservative one is used which provides an average available heating power of 48kW.

2.3.5. Deep Geothermal

Kilmarnock sits on geological formations belonging to the Scottish Coal Measures Group which forms the bedrock for most of the Midland Valley (BGS, 2018). Although the deep geology is not clearly understood, this sedimentary bedrock may extend as far as 8000m (AECOM, 2013b). The formations comprise repeating layers of sandstone and siltstone with thinner layers of mudstone and have thicknesses ranging from a few hundred meters to thousands of meters (BGS and SEPA, 2015). The siltstone is largely impermeable and so distinct and separate aquifers may exist within the porous and permeable sandstone strata.

Geothermal Resource: Method and Data

The Heat in Place method was used for this assessment (Franco and Donatini, 2017). This calculates the weighted energy contained in the bedrock and groundwater above a reference value, T_{ref}, which was taken to be the average annual air temperature (10°C). The normalised energy contained in the aquifer is found using Equation 8.

$$q = \left(\varphi\rho_w c_{p,w} + (\varphi - 1)\rho_b c_{p,b}\right) \cdot d \cdot \left(T_{aq} - T_{ref}\right) \qquad \text{Equation 8.}$$

Where ρ and c_p are the weighted density and specific heat capacity of the water and bedrock; φ is the bedrock porosity; and T_{aq} is the aquifer temperature. The heat of the bedrock, which cannot be directly abstracted, will transfer to water that replaces the abstracted water (Franco and Donatini, 2017). This replenishment involves complex ground flows and is therefore out with the scope of this project. Instead, it is assumed that only the water's heat can be exploited, and Equation 8 was modified accordingly.

The temperature of the aquifer is central to the available resource. Although the geothermal heat flux across Scotland has not been extensively researched, AECOM research suggests that the temperature gradient increases with depth. Three linear profiles corresponding to different depths are proposed as shown in Figure 2.10.

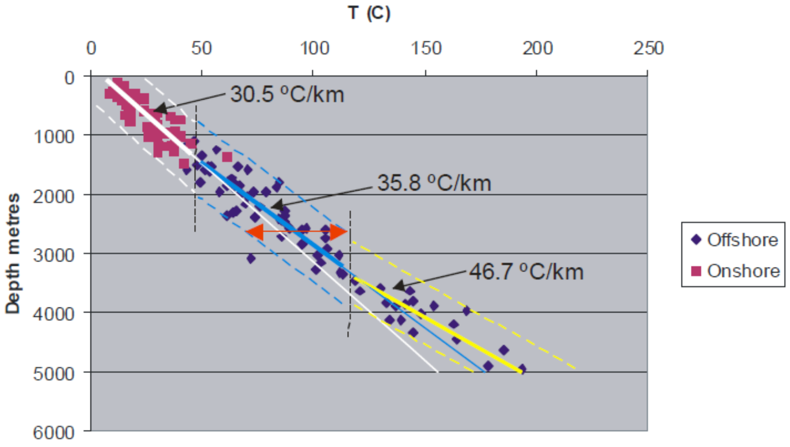

Figure 2.10: Scottish geothermal temperature gradients (from AECOM, 2013b).

Geothermal Resource: Results

A conservative estimate of 50°C was used for the 2000m geothermal well. According to the proposed temperature gradients, however, it could be closer to 63.7°C. A conservative value of 200m was taken for the sandstone thickness and its porosity was taken as $\varphi = 0.12$ (BGS and SEPA, 2015). Physical properties of the bedrock and water were taken from (AECOM, 2013b) which suggested: $\rho_w = 1000$ kg/m3, $c_{p,w} = 4.18$ kJ/kgK, $\rho_b = 2500$ kg/m3 and $c_{p,b} = 0.84$ kJ/kgK.

Based on these values, the total heat contained in the aquifer was 5220 GWh/km^2. Considering the aquifer water only, the resource was 1115 GWh/km^2.

The potential heating power of the aquifer depends on the natural abstraction flowrate and temperature drop achieved. The temperature drop across a HP was assumed to be 40°C – to bring the water to ambient conditions. Common flowrates for aquifers in this geology are 5-15 kg/s (AECOM, 2013b). The heating potential, using a conservative flowrate, was determined to be 840kW. At this constant rate, the lifespan of the well would exceed 150 years/km^2.

2.3.6. Disused Mine Workings

Flooded mine workings provide a more accessible form of geothermal energy. Figure 2.11 indicates the mine-shafts across Kilmarnock. The depth of these does not exceed approximately 200-300m (AECOM, 2013b) and the temperature of entrapped water is correspondingly lower at approximately 10-15°C.

Since information regarding the state of the mine shafts and their subterranean connections was not available, this resource was scoped out of the investigation. It should, however, form the focus of future work into an accessible and reliable local heat resource.

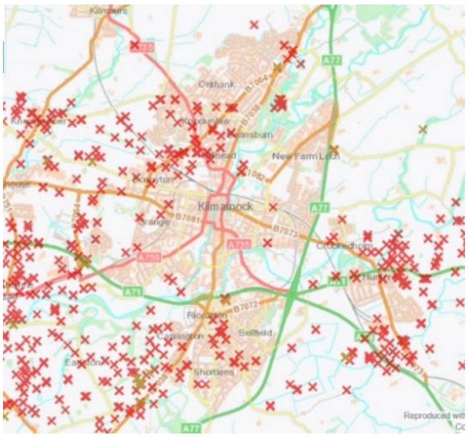

Figure 2.11: Mine shafts across Kilmarnock (Coal Authority, 2018)

2.4 Chapter Summary

HALO Kilmarnock was introduced in this chapter and all information available to the author was presented. The development was located within the local area which was discussed in terms of its demographics, buildings and energy use.

Heat demands for each building type at HALO were determined via benchmarks and these were checked against the energy performance of existing buildings in the area. These annual demands were then fitted to representative data to derive hourly heat demand profiles. Local renewable heat resources were also identified and quantified.

The next chapter is concerned with potential low and ultra-low, renewably powered district heating networks. The demand and supply profiles from this chapter are compared to establish reliable supply options. Potential networks for HALO are then conceived and discussed before a decision on the final networks to model is taken.

Chapter 3: Network Options

Using the site demand profile and available resources from Section 2, appropriate supply technologies are now identified. In this section, the seasonal matching of supply and demand for each technology is investigated. Following this, potential network configurations are presented and discussed. The scoping-out of several of these networks is then justified. The section ends with a detailed discussion of the layout and control of the TRNSYS models developed.

3.1 Supply Technology

In the following sections, the temporal supply available from each technology is compared to the temporal demand of the site. For every hour in the year, the demand profiles, from Section 2.2, and supply profiles, from Section 2.3, were directly compared. From this, the average monthly supply and demand, alongside the number of hours in the month when supply was instantaneously insufficient were determined.

Solar Thermal

It was assumed that the total roof space at HALO equalled half of the aggregate GIA of all buildings. It was further assumed that 20% of the total roof area could be turned over to solar thermal panels with an efficiency of 70%. The hourly heat supply profile was scaled to account for these assumptions and the results are presented in Figure 3.1.

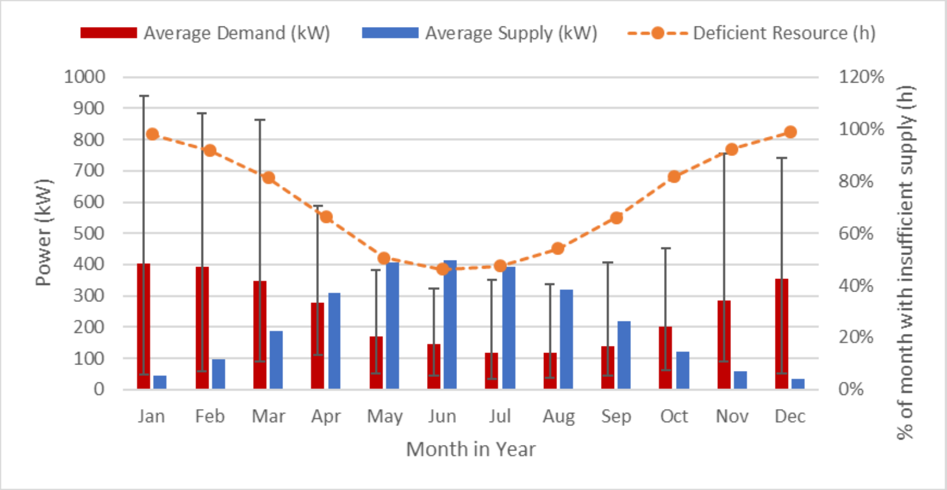

Figure 3.1: Solar thermal supply-demand matching

The seasonal discrepancy between the solar resource and heat demand is shown by these results. In the peak heating season, the monthly resource was approximately 10-20% of total demand whereas in summer it outstripped demand by double. However, because of the daily cycle of solar radiation, even in summer the resource only met demand 50% of the time.

It is noted that thermal storage could provide significant support, especially in summer, to this technology. This is also true in winter when the resource was insufficient nearly 100% of the time. However, for the purposes of this project, the resource deficiency in the peak heating season rendered it only useful as a supplementary technology.

River Source Heat Pumps

The ‘minimum’ profile from Section 2.3.3 was used in this comparison to capture a worst-case scenario. Plots are presented in Figure 3.2 for each month of the year.

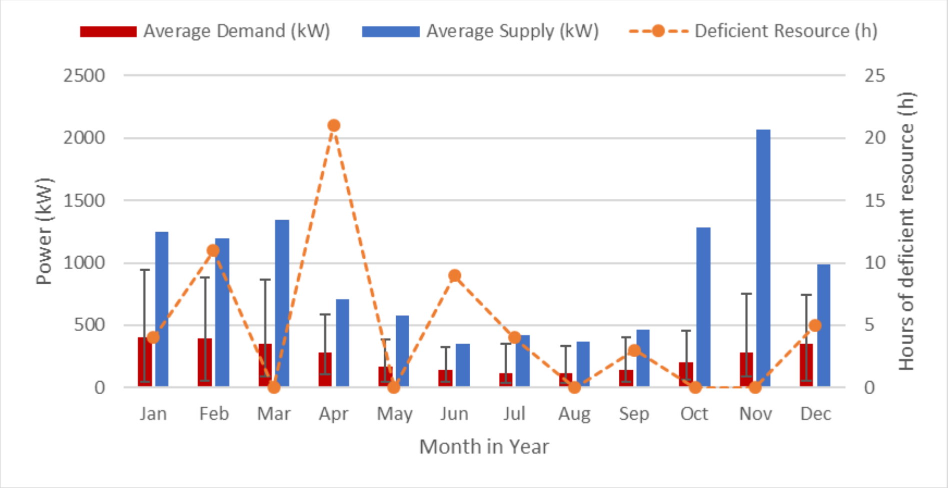

Figure 3.2: River resource supply-demand matching

In each month, the average available supply was at least twice the average demand. There were points in most months however when the instantaneous extractable power was insufficient. In the worst month (April) the number of periods when supply was insufficient corresponded to roughly 3% of the month. The longest consecutive period of under supply occurred in here and lasted for 7 hours. During this period, the available resource was still able to meet 80% of the demand.

Deep Geothermal

The geothermal resource, unlike those discussed so far, was assumed to be unvarying. In Figure 3.3, the supply power is represented by a single horizontal line at 840kW as reported previously.

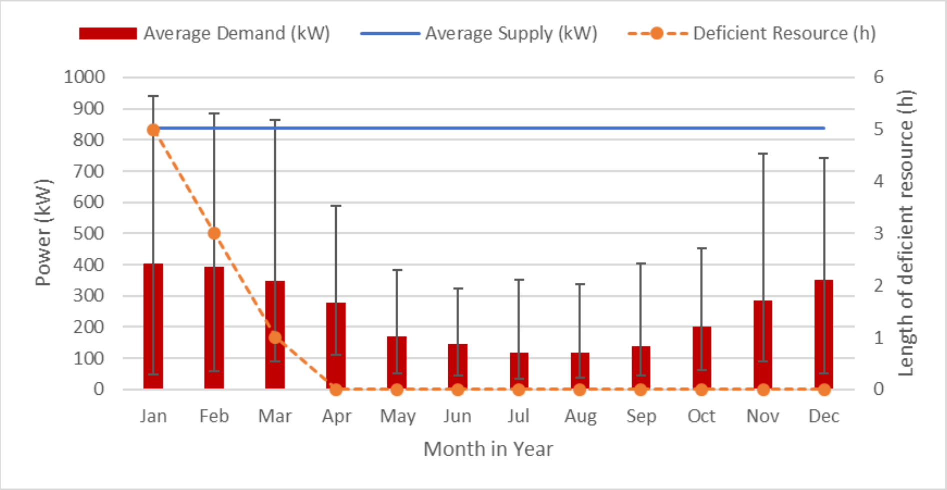

Figure 3.3: Geothermal resource supply-demand matching

The resource is capable of meeting demand essentially year-round. Only during 9 hours in the year was the instantaneous heat demand greater than the supply power. A geothermal powered heat pump or heat exchanger would therefore provide the most reliable heat resource to the HALO project.

Waste Water Resource

Waste water heat recovery could not be used as a principal supply technology as it relies on the prior generation of heat. For the results in Figure 3.4, the hours of insufficient power are not presented. Instead the percentage of monthly demands covered by this resource are provided. The recovery power was 48kW as reported in previously.

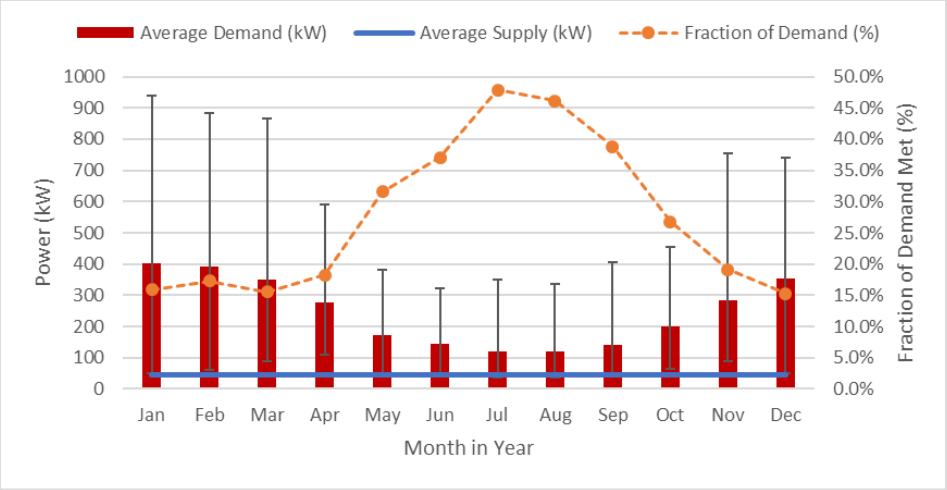

Figure 3.4: WWHR coverage of demand

As with solar thermal, waste water heat recovery cannot be used as a baseload technology. However, it could provide roughly 15% of demand year-round and almost half of total demand in the summer months.

3.2 Network Options

3.2.1. Requirements of the Network

There are myriad systems which could be installed to provide for the heat requirements at the HALO project. For this project, consideration of building-located heat supply was scoped out in favour of DHNs. This decision was based both on the lack of information regarding the building forms and the Scottish Government's policy initiatives to support and develop district heating networks. The form of the network – the supply technologies, circuit and operational characteristics – are within scope.

Due to the minimal cooling demands of the development, the incorporation of a cooling service was deemed unnecessary. Although the Innovation Hub and speculative offices may have air-conditioning requirements in the summer months, the commissioning of a network to meet these temporary demands was thought to be cost-ineffective. Instead, the provision of DHW and space heating were essential services.

Asides the provision of these two heat services, the principal requirements of the systems are to be resilient and low-carbon. In the following pages, several feasible district heating configurations are presented. The combination of plant and general operating conditions, alongside the advantages and drawbacks of each are discussed.

3.2.2. Network Concepts

I. GSHP + Solar Thermal + Seasonal Storage

A convenient exploitable synergy exists between GSHP and solar thermal panels. Although the ground resource may be small, it provides a good storage medium for thermal energy. For this system, solar thermal panels are installed and allowed to operate across the year. At times of excess production, the resource is redirected to the ground for storage. GSHPs are used to exploit this when required (MacKay, 2009).

The whole system entails substantial capital costs related to the drilling of ground boreholes, the installation of solar thermal panels alongside the installation of ground source heat pumps and the remaining infrastructure for a district heating network. Also the ground water flows will remove stored heat if they are present. As this is unknown, the network cannot be accurately modelled. The complexity of the system would pose a modelling challenge as well.

II. Deep Geothermal HP

Aquifer heat is the largest and most consistent of the assessed resources. In terms of developing a robust system the use of geothermal energy provides supply certainty. It was predicted that water from a geothermal aquifer would exist at a temperature of 50°C. This is just below the temperature at which DHW can be directly produced via heat exchangers. To overcome this, a heat pump in the EC could raise the temperature.

The main strength of this proposal lies in the reliable and plentiful heat that a deep geothermal aquifer could provide. The small temperature rise required to achieve useful heat means that a minimal amount of electricity would be expended in the heat pump. The weakness in this suggestion is the uncertainty surrounding the existence of a geothermal aquifer under the site, and the large capital cost required to access it. However, this cost is offset somewhat by the lifespan of the well and the interest of the Scottish Government in exploiting this resource in Scotland.

III. Geothermal HX + DHW Boost

An alternative suggestion utilising a deep-geothermal well is to decentralise the heat pumps. In this instance, the abstracted geothermal water would be passed through a heat exchanger, and its heat would transfer to the DHN. The circuit supply temperature would be approximately 40-45°C making it a ULTDH system with the requirement of booster heating at the point of use. This proposal avoids the requirement of installing a central heat pump but incurs additional plant costs at the user end. As with the previous system, the main issues surround the existence and cost of accessing a potential deep geothermal aquifer.

IV. RSHP + DHW Boost

To avoid the large capital expense incurred by a deep borehole, the second most reliable resource available is heat from the River Irvine. It has been shown that, in a worst-case scenario, this resource could supply heat for all but a few hours in the year. The relatively stable temperatures of the river annually mean that a HP could operate with a consistent and high COP. Schemes such as Drammen in Norway use RSHPs to extract heat from a fjord. This heat is used to produce 75°C water for use in a district heating system and the system reports an annual COP of 3.05 (EHPA, 2015). Alternatively, the temperature of the river water means it is well suited for ULTDH.

Although the high cost of a geothermal borehole is avoided with this system, significant costs are associated with accessing the resource. Pipework (likely buried), would be required to transport the river water to site. This would incur operational costs with respect to pumping requirements. The abstraction of river water also poses a challenge around the treatment of it (after abstraction and before return) to ensure that hazardous particles and chemicals were not introduced either to the network or the environment.

V. ULTDH + Distributed Supply (prosumers)

ULTDH networks allow the exploitation of substantial renewable heat resources which are not economical or feasible within higher temperature systems. Therefore, distributed renewable heat systems such as building-sited heat pumps and solar thermal panels could be integrated into a single network. It is likely that future DHN will have greater degrees of distributed production and agents connected to the network may increasingly become ‘prosumers’.

At HALO, it would be possible to equip a variety of buildings distributed across the site with several different technologies. Such an approach would add resilience to the system through the incorporation of multiple heat sources and add flexibility in terms of back-up and optional capacity. Such a network would pose a substantial modelling and control challenge however.

VI. ULTDH + WWHR

Another low-temperature resource that can be readily incorporated into a low temperature network is sewer heat. In a similar vein to the previous suggestion this plant could add resilience to the system. If the sewers exploited were those to which the buildings at HALO were connected, then the periods of high hot water demand would generally coincide with the periods with the largest waste water resource, and the best performance of the sewer network heat pumps. Such an addition to the network introduces a ‘circular economy’ aspect and adheres to the original principles of district heating with its utilisation of a waste heat resource.

3.3 Configurations for Investigation

Although each of the systems proposed have potential for further investigated, only two were taken forward. Available time and the capabilities of TRNSYS imposed limits on both the number of networks investigated and the level of complexity they could be modelled to. As a central aim of this work is to compare the performance, economics and other attendant issues of traditional district heating, 4GDH and ULTDH, networks it was decided to focus on systems for which these could be easily investigated.

3.3.1. Network Definitions

Ultimately, the energy source for either network is somewhat interchangeable although certain technologies lend themselves more to certain networks. Due to their long and short-term reliability, the supply technologies chosen for the final networks were river source heat pumps and geothermal heat pumps. These two resources fit well to the two network types. The use of a central HP in both networks further allows a comparison between these two network concepts to be undertaken.

The first network investigated comprises a geothermally powered heat pump in a traditional district heating network (operating above 55°C). This heat pump is to be in a central EC with a back-up gas boiler. A thermal store will provide short term balancing of the system through the storage and discharge of surplus or deficient heat, respectively. The buried pipework transports the heat to HIUs in each building. It is assumed that both DHW and space heating requirements will be provided instantaneously via high-efficiency heat exchangers.

For the second network, a RSHP will be used to provide ultra-low temperature water to the district heating network (at 45°C) supported by a back-up gas boiler. River water will be conveyed to this central HP through buried pipes. To introduce an alteration to the networks, no thermal storage will be included and instead the HP will modulate to meet demand. This should lower losses further in the system. On the building side, it is assumed that low-temperature radiators will be used. This avoids the undesirable high return temperatures of underfloor heating.

The boost heating required in this network for DHW will be provided in different ways: micro heat pumps and direct electric heating. These will extract heat from the district network through high efficiency heat exchangers (before the boost electric heating) or directly (by using the district network as both source and sink for the HP). In the HP system, a high efficiency heat exchanger will be used for the instantaneous production of DHW. Investigating both boost approaches allows insight into the relative merits of each in terms of energy requirements, performance and additional capital costs. Further elements could be introduced to this network such as sewer network heat recovery or building located renewable heat installation, but for the present project this is out of scope. These investigations are left as future work.

3.3.2. Network Layout

As the two networks both produce heat centrally, the distribution network will be common to both. Optimal network layout is based upon balancing capital costs against pumping requirements and heat losses. It is desirable to have as short a network as possible since, for a given heat demand, this improves the linear heat density. However, this is tempered by the ground conditions for excavation and installation.

The preference is to install pipework in soft ground which can be easily accessed. Since HALO is located on a brownfield site with no buildings currently, the route of a network is more open. It is assumed here that the route taken by the network will be as direct as possible whilst remaining in open area for accessibility. A provisional plan of the network is presented in Figure 3.5.

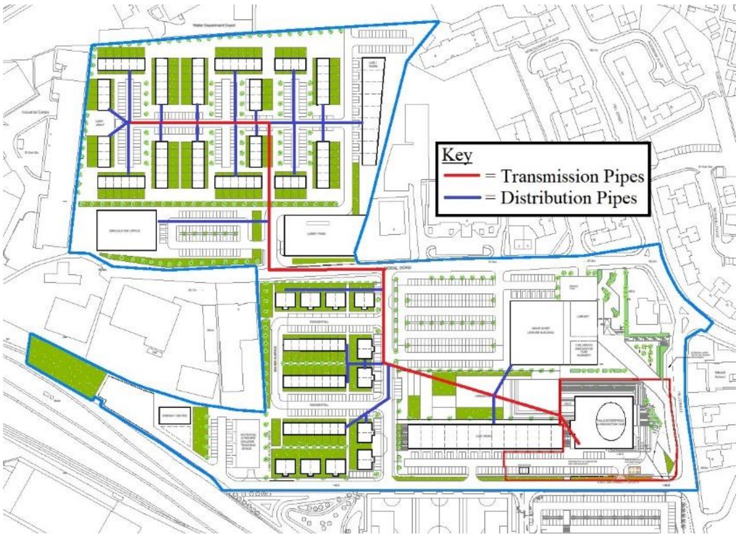

Figure 3.5: Provisional DHN pipework layout

The sizing and specification of the pipework will not be fully addressed in this project. Such decisions are based on the relative trade-off between installation and running expenses. However, it is assumed that twin pipes will be installed across the network and these will be Series 2 type. For the purposes of modelling, the pipe diameters will be set such that the flow speed of the transported fluid does not exceed 2 m/s. The pipework here comprises 520m of transmission pipes and 780m of distribution pipes (each for flow and return). The linear heat density is therefore 1.65MW/m.

3.3.3. Benchmark Network Costs

The financial analyses, presented later in Section 5, were based on the TRNSYS results and likely capital and operational costs associated with the systems. Benchmark costings are provided in Table 3.1. These values were from (DECC, 2015) unless otherwise stated. Limited data existed regarding the cost of a geothermal borehole and so the most appropriate value from (AECOM, 2013a) was used. To be conservative, the cost of laying the uninsulated river abstraction pipework was assumed to be the same as the benchmark cost for insulated buried pipework.

Table 3.1: Benchmark district heating network costs

Cost	Phase	Rate	Relevant Network
Geothermal Borehole	CAPEX	£8m	Geo + HP
Heat Pumps	CAPEX	£700/kW[iii]	All
Gas Boiler	CAPEX	£45/kW[iv]	
Thermal Store	CAPEX	£843/m^3	Geo + HP
Buried Pipework	CAPEX	£468/m	All
River Pipework	CAPEX	£468/m	LTDH
HIUs	CAPEX	£1075/dwelling	All
Heat Meter/Substation	CAPEX	£3343/building	All
Maintenance (Heat Network, HIUs and Heat Meters)	OPEX	£13/MWh	All
Staff and Business Rates	OPEX	£22.90/MWh	All

3.4 TRNSYS Models

Two principal TRNSYS models were developed to investigate the main aims of this work. The first, geothermal powered network was used to assess the impact of reducing circuit temperatures from contemporary values (75°C) to 4GDH values (55°C). The second network, using the RSHP, was used to assess the impact of lowering temperatures further to ULTDH (45°C). Five models were derived from these two. The names used throughout the remainder of this work are:

1. Geo (75°C);
2. Geo (65°C);
3. Geo (4GDH);

[iii] Taken from (Cowan, 2018)

[iv] Taken from (Poyry, 2009)

4. ULTDH + Elec; and,
5. ULTDH + HP.

3.4.1. Geothermal District Heating Network Model

The layout of the geothermal district heating model is provided in Figure 3.6. The network is composed of two circuits – supply and distribution – which are balanced and connected by a stratified thermal store. In the figure, the TRNSYS components are connected by black solid lines and red dashed line. These represent the physical connections between components and data flows, respectively.

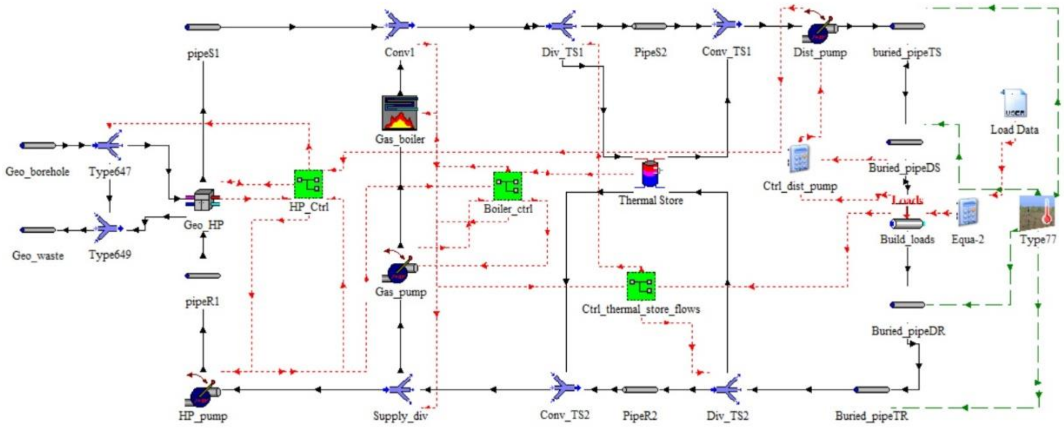

Figure 3.6: Geothermal model schematic

The distribution circuit (right) was composed of pipework, pumps and flow-loads. The flow-loads can be though to represent simplified HIUs where heat is extracted from the network. The size limits of TRNSYS simulations precluded detailed modelling of each load and all loading on the system was introduced through a single load point.

The distribution network was modelled through two flow and flow return pipes (one for both transmission and distribution as presented in Figure 3.6). The surrounding environmental temperature was linked to a ground temperature model component. There are no available TRNSYS pipe models which link the adjacent flow and return pipes spatially to each other and so their thermodynamic interactions are not captured by this model.

The delivery of adequate heat and the maintenance of an adequate flow-return temperature differential were ensured by the modulation of the distribution mass flowrate. The pump was sized such that, at peak demand, the temperature differential over the load was 20°C. The pump flowrate was controlled based on the fraction of peak demand being removed at each time step.

The supply circuit (left) introduced heat to the system via the geothermal powered HP and back-up gas boiler. TRNSYS heat pumps modules do not physically model the thermodynamic processes of a real system and instead interpolate between supplied operational data. For these simulations, data for a high temperature heat pump were used. The heat pump had a maximum flow temperature of 72°C and heating capacity of 18.7kW (Viessmann, 2017). The data was scaled to represent a modular arrangement. Large high temperature heat pumps could exhibit significantly different operational performance, however.

Within the model, maximising the heat pumps operating time was desired. The heat pump switched off only when the main flowline temperature exceeded 10°C above the desired flow temperature. A control routine was implemented such that once triggered, the heat pump would remain inactive until the main flowline temperature had dropped by at least 15°C. This avoided rapid cycling of the heat pump. As the TRNSYS heat pump component could not be readily modulated, its outflow temperature was maintained by modulating the flowrate through it. This was done in an analogous manner to the distribution flowrate control.

The gas boiler provided supplementary heat when the heat pump output was deficient. It was controlled to remain off until the average temperature of the thermal store dropped to 10°C below the desired flow-temperature. Once activated, a control loop was used to hold the boiler on until the thermal store temperature was 5°C above the desired flow temperature. When on, the boiler component modulates its heat injection to maintain a setpoint temperature. For this model, a set flowrate entered the boiler when on and this was raised to 5°C above the circuits supply temperature.

The thermal store performed two important functions. First, it stored excess heat for later release, which reduced the modulation requirements of the supply plant, and, secondly, it balanced the flowrates of the two circuits. A 50m^3 thermal store was used in the model with the default TRNSYS loss coefficient – as no real component data could be accessed. The charging and discharging of the store occurred passively and was determined by the relative flowrates in each half circuit. The excess flow of the circuit with the higher flowrate was diverted to the store and, once through, re-entered the opposite side of that circuit.

3.4.2. Ultra-Low Temperature District Heating Model

The ULTDH model took a different form to the geothermal network. The overall layout of the model is provided in Figure 3.7. It was composed of a main distribution circuit – comprising the central RSHP, distribution pipework and pumps – and secondary building side circuits which extracted heat from the network to provide space heating and DHW separately. As in the previous model, one load was used to represent all loading on the network.

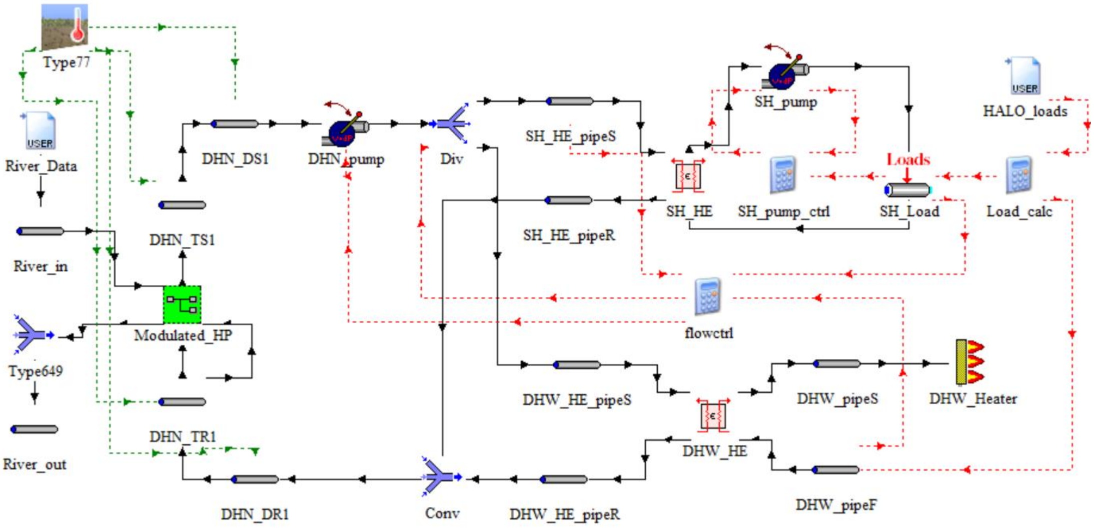

Figure 3.7: ULTDH model schematic

Since no thermal store was included in the main distribution circuit, modulation of the heat pump's output power was essential. Without modulation, the heat pump could provide all or none of its heat capacity which presented a challenge to controlling its output temperature and, consequently, the supply temperature. A work around was developed which introduced artificial heat pump modulation.

In this model, ten heat pumps were connected in parallel with incrementally increasing rated capacities. Each heat pump was associated with a distinct range of heating powers within which its capacity resided. The heat required to raise the incoming flow's temperature to the desired flow temperature was calculated and a single heat pump was determined through which all the flow passed, at that timestep. A degree of overshoot and undershoot intrinsically existed with this denary approach, and so a cooling and heating module were included after the heat pump to mitigate extreme temperature occurrences.

Since supplementary heat was required for hot water production, it was necessary to split the loading for these two services within this model. This was done by selecting a day outside the heating season with low heating demand. It was assumed that this profile represented a hot water only load and so this was subtracted from every other day to give annual space heating and domestic hot water profiles. Space heating was removed from the network via a constant effectiveness heat exchanger. The flowrate through the hot side of the heat exchanger was controlled to transfer sufficient heat for the instantaneous space heating demand – determined by the flowrate and required temperature rise of the cold-side return water.

In the ULTDH model with auxiliary electric heating, a similar approach was used to preheat the DHW before the booster heating. This was done through a separate constant effectiveness heat exchanger and the hot-side flowrate was similarly modulated depending on the demand side requirements. A generic heating module was included after this preheat, to raise the water temperature to 50°C.

For the ULTDH model with booster heat pump, the hot water was fully provided by a micro-heat pump. Distribution water at 45°C was used in both the condenser and evaporator. The mass flowrates were controlled so that cooled outlet stream was at the desired return temperature. As modulation of the heat pump was similarly not possible, a thermal store was included. The raised temperature stream passed through a heat exchanger and added heat to the DHW stream passing through the store. This store acted as a dummy element with zero losses or auxiliary heat input. The overriding requirement was that the outflow and return water temperatures matched the requirements of the network.

3.5 Chapter Summary

This chapter began by comparing the supply and demand of the renewable resources assessed in Chapter 2. From this, resilient supply options were determined. It was shown that deep-geothermal and river-source heat were the most consistent and reliable of all resources.

Several network concepts were then presented. Through consideration of the supply technology, the limitations of modelling and the aims of this project, these options were reduced to two basic models. The networks to be modelled were clearly defined, then benchmark costs and a pipe layout design were provided.

The chapter finished with a discussion of the TRNSYS models with a particular focus on the control used in the networks. In the next chapter, the results of the simulations and the principal analyses of this work are presented.

Chapter 4: Modelling Results

4.1 Analyses Conducted

4.1.1. Questions and Analyses

With the two TRNSYS models presented in Section 3.4, simulations spanning a year were conducted at 5-minute timesteps to ascertain the performance of the 5 derived district heating networks. Multiple parameters are output from each TRNSYS component which allows its state and performance to be determined. Amongst the important parameters to extract here were the temperatures and flowrates around the network, the heat transfer processes into or out of relevant components and the operational parameters such as control signals and plant efficiencies.

From these output parameters, post-processing allowed multiple analyses to be conducted. Initially, the detailed transient behaviour of each network was investigated. The circuit properties were interrogated to understand and verify the performance of each model. This was primarily conducted by reviewing plots in different seasonal periods and assessing the average and peak values of certain quantities.

The substantive analyses conducted resulted in the production of performance metrics and related to systemic features such as heat losses, fuel requirements, hours of operation and under-performance, running costs and overall efficiencies. These metrics were the basis for comparing each of the 5 simulated systems. Besides the physical performance of the networks, the environmental emissions associated with their operation and a financial analysis of the overall systems costs were undertaken. The results of these are provided in Section 5.

The models developed could be used to answer many other research questions. The effects of alternate operating schedules and conditions; the integration of distributed supply technologies; or the impact of demand side management, are a few of the further questions that are left to future work. For the purposes of this project, the focus remains on ascertaining the financial, environmental and operational impact of reducing flow temperatures to 55°C in traditional systems; and, comparing the relative merits of ultra-low temperature district heating with auxiliary heaters against higher temperature networks.

4.1.2. TRNSYS Limitations

Before discussing the results, certain issues surrounding the functionality of TRNSYS will be presented. Although a powerful and versatile tool, especially for the simulation of dynamic thermal systems, as with any software there are drawbacks to its use. Some of these are presented below.

Solver Type

The ‘input-output’ approach of TRNSYS is reflected in the solution method which occurs sequentially. This contrasts with a simultaneous approach where the entire system matrix equation is solved simultaneously. During a solution step in TRNSYS, the internal calculations associated with each component are solved successively. This means that the output of component A is calculated before being inputted to component B during the same time step. For a circuit system this can lead to convergence issues when the final component output is returned to the first component to check for convergence. With poorly set control logic, this has proven at times to be problematic.

Component and System Properties

Although a transient simulation tool, TRNSYS is not a fully dynamic piece of software. That is, many of a model’s properties are defined before the commencement of a simulation and are not updated during the simulation to reflect the present state of the system. The variation of fundamental thermal properties (e.g. density, thermal conductivity and specific heat capacity) with transient state variables (e.g. temperature) is omitted from the simulation.

A related issue is the omission of fluid mechanics in the models. A component’s internal mathematics deals principally with its thermodynamic behaviour and not its mechanical response. For example, with the pump components control can be imposed to regulate the flowrate but the actual associated pump work is not determined. In place, either a predefined pressure drop, or a single system-curve/pump curve or a pre-defined relationship for power against flowrate must be given. None of these approaches satisfactorily capture the transient mechanical behaviour of a complex system.

Component Drawbacks

The components are necessarily limited in number and in complexity. Many additional ones are available through the TESS component library which extend the options and capabilities of modelling on TRNSYS. The mathematics underpinning all components is simplified however and uses analytical relationships and ordinary differential equations to represent complex physics which stem from the solution of the governing partial derivative equations presented in Section 1.3.1.

Furthermore, the user is somewhat constrained by the workings and logic of the supplied components. Certain built-in component features (e.g. the in-ability to modulate the output power of heat pumps) can introduce additional complexity in the design of the model and necessitate the introduction of work-arounds, as has been done in this project. Although not open-source, it is possible to programme personalised components which allows these issues to be somewhat overcome. However, with time limitations this approach is not necessarily available.

Limited Outputs

A final issue relates to the permitted size of a simulation. The maximum number of several model features (e.g. equations and outputs) are written into the source code and cannot be easily altered. Although for simple systems this presents no problem, with complex networks such as those investigated here, these limitations impose simplifications on the model. It is, however, acknowledged that with increasing model size, the computational demand increases exponentially. Thus, these limits may also limit computation time and reduce convergence issues.

4.2 Results of Geothermal Network

In this section, simulation results from the geothermal models are presented. To begin, the operation of the model over a typical winter and summer week is presented. Following this, performance metrics are discussed regarding the efficiency, emissions and costs of the systems. To end the section, the impact of the ‘single load’ simplification is assessed with respect to a ‘three load’ model.

4.2.1. Model Behaviour

The graphs in the following section provide the system’s typical operation in the heating and non-heating seasons. In Figure 4.1, the main flow and return temperatures, and the mass flowrate through the distribution circuit are given.

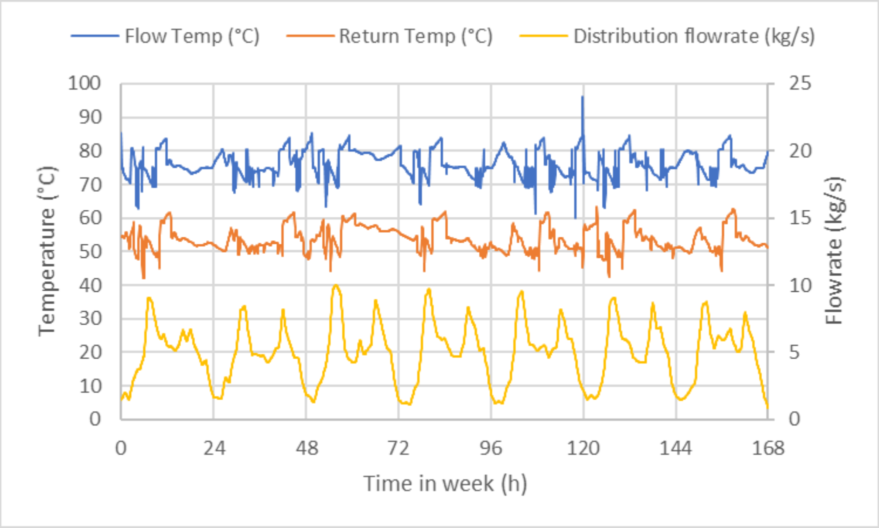

Figure 4.1: Distribution temperatures and flowrates (winter)

It is apparent that the flowrate successfully modulated to maintain a 20°C temperature differential across the circuit – evidenced by the near constant separation of the temperatures over the week. The two plots are slightly offset due to the circulation time lag. Although the temperatures fluctuate, they are predominantly in the 70-80°C and 50-60°C ranges.

The fluctuations are caused by a number of factors: the limited modulation of the heat pump caused excessive or insufficient heat injection which impacted the main outflow temperature; the instantaneous starting and stopping of the heat pump and boiler sometimes produced unrealistic rates of change; and the change from charging to discharging of the thermal store impacted the mixed flow temperature.

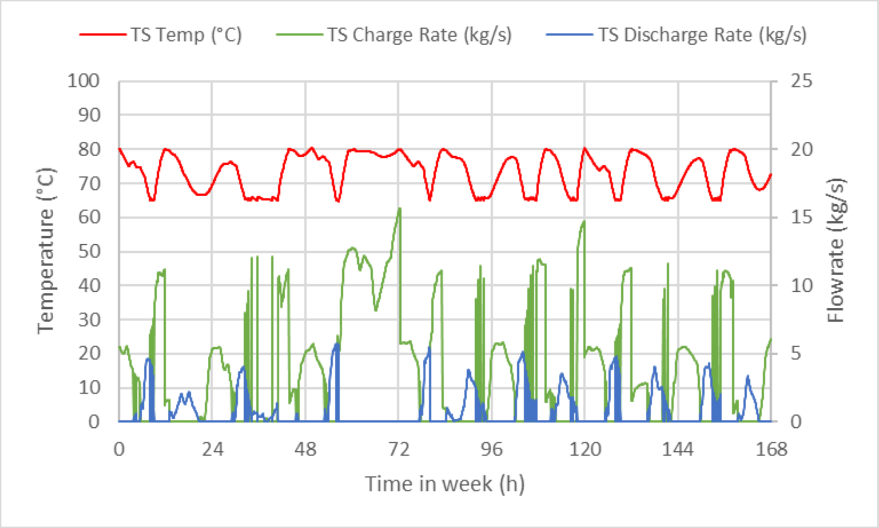

Figure 4.2: Thermal store operation (winter)

The thermal store's operation over the same period is provided in Figure 4.2. Both the average temperature plot and the charging/discharging plots reveal the utilisation of the thermal store for balancing and storage purposes. The periods of charging are considerably longer (4-20hrs) than the periods of discharging (2-4hrs). A central reason for this is the rapid decrease in thermal store temperature when discharging occurs.

Most discharging periods end with a change to rapid re-charging. In these periods, the temperature of the store reached 65°C and the gas boiler was triggered. In most cases, the gas boiler was required to recharge the store, however, sometimes the heat pump achieved this. These times were typified by a slower temperature increase and a curved as opposed to rapid increase in flowrate e.g. the early morning around, 24h, 96h and 144h in Figure 4.2.

This behaviour is supported by the plots in Figure 4.3, where the heat input of the supply plant is presented. Only the heat pump was in operation during the aforementioned periods. These plots also reveal the primary role the heat pump had in the heat supply. The heat pump provided almost 400kW of heat continuously over the week. The gas boiler conversely operated for limited periods of 3-5 hours, notably during mid-morning periods when the thermal store had been depleted from morning activities. Returning to the flow temperature fluctuations in Figure 4.1, the most extreme increases and decreases occurred when the gas boiler switched on and off.

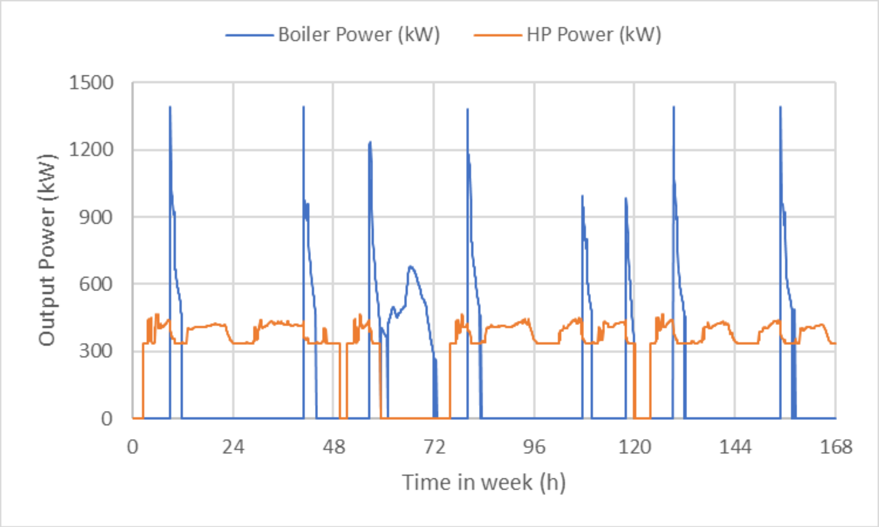

Figure 4.3: Heating plant operation (winter)

The only significant period of inactivity for the heat pump was from 60-74h. At this point, the gas boiler was recharging the thermal store and caused the main flow temperature to reach 85°C. This triggered the heat pump to switch off. However, the flow temperature then remained just under 80°C and so the restart temperature of the heat pump was not reached. At 72h the boiler switched off and the flow temperature dropped until the heat pump's restart temperature was reached. This presents an issue in the control routines and these could be amended to give preference to heat pump operation over the gas boiler.

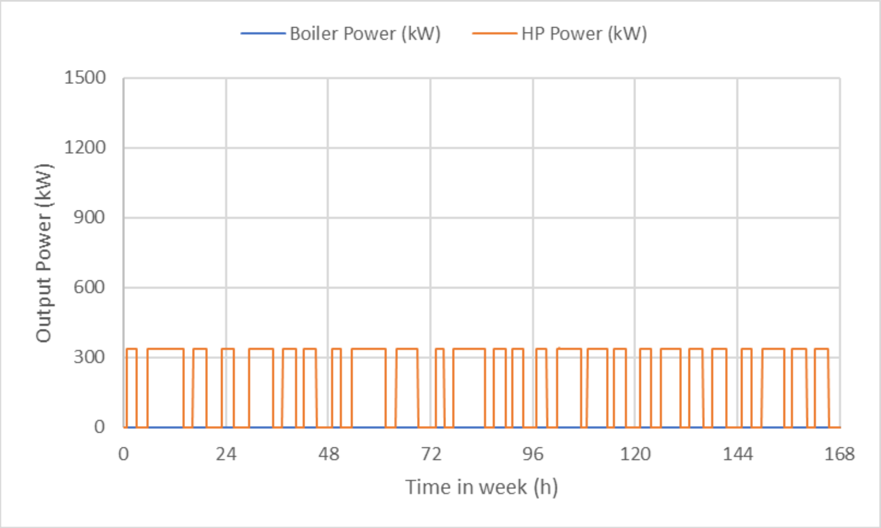

Figure 4.4: Heating plant operation (summer)

In summer, the operation of the system was markedly different. Principally this arose from the lower heat demands in this period which meant that the heat pump had sufficient capacity to meet the loading. In Figure 4.4, this operation is presented. The heat pump cycles on and off three to four times a day. Operational periods last for several hours and are separated by 2-3 hour periods. The boiler was unused for approximately seven spring, summer and autumn months during the year simulation.

Without control loop to hold the heat pump off for a time, it cycled repeated throughout this period over very short periods (every 1-2 timesteps). This behaviour is undesirable in a real system due to the wear it causes in components and is undesirable in the simulation due to the numerical instability it introduced to the solution.

The cycling of the heat pump impacted the main flow temperature of the distribution network which fluctuated more during the summer months and took a higher average value. The flow temperature was therefore more periodic here and took the shape of repeated crenellations, presented in Figure 4.5. The temperature differential between flow are return remained constant across this period as in winter and the flowrates were generally lower which was a proxy for the lower heat demand.

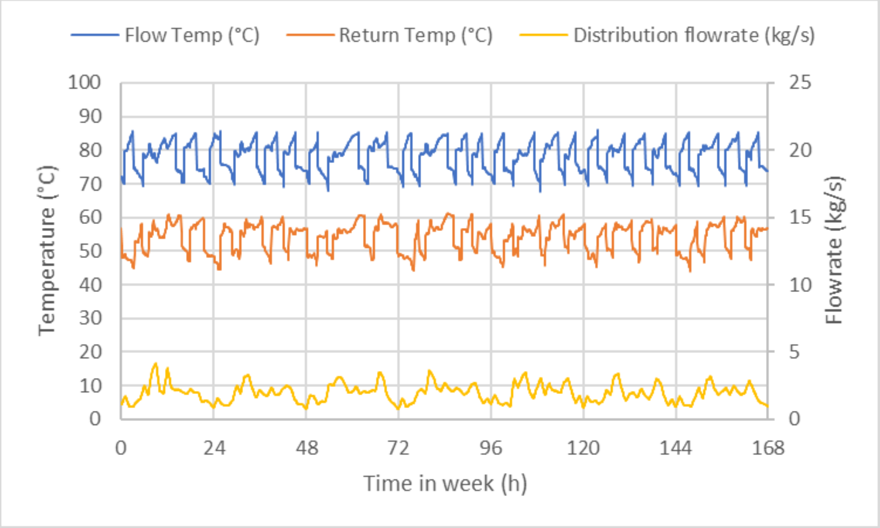

Figure 4.5: Distribution temperatures and flowrates (summer)

A consequence of the lower flowrate was the underutilisation of the thermal store. Across the summer week, the thermal store did not discharge once – indicating the supply flowrate was permanently greater than the distribution flowrate. This meant that the thermal store's temperature was on average higher than in winter as shown in Figure 4.6. Yet it still varied between roughly 75-80°C. These drops were caused, however, by colder supply water entering the store during periods of heat pump inactivity and not by the extraction of heat for a useful purpose.

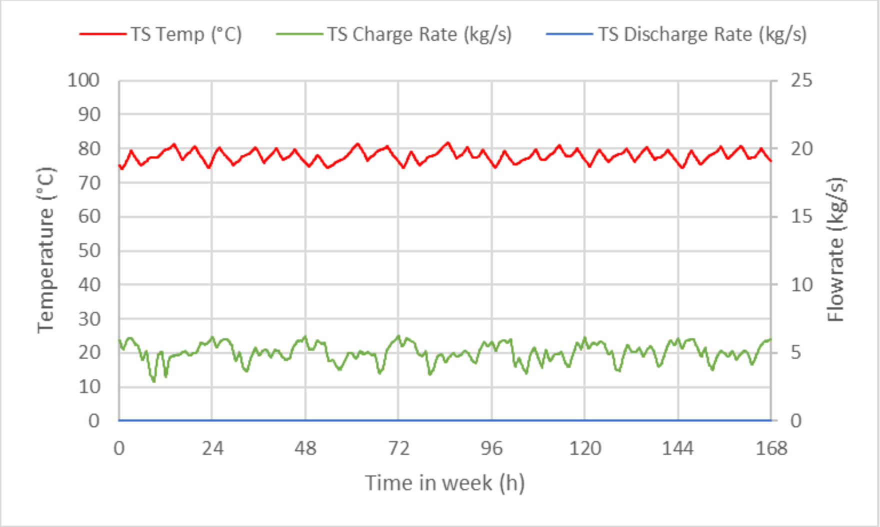

Figure 4.6: Thermal store operation (summer)

The operation of the model was sensible, and the performance was like that of real systems such as the West Whitlawburn biomass district heating network in Glasgow[v]. The control applied to the system was necessarily simplified. It was developed using the basic aim of ensuring adequate heat supply. More complex control can be applied in real systems, making decisions based on multiple sensed conditions around the network. However, improving the control is left for future work. This could involve the TRNSYS-MatLab interface or different seasonal operating regimes.

4.2.2. Performance Metrics

Having outlined the overall operation of the geothermal district heating model, this section presents performance indicators for systems will flow temperatures from 75°C to 4GDH at 55°C.

The geothermal well's flowrate is determinative to its lifetime. With a flowrate of 5 kg/s, a lifetime of 150 years was estimated in Section 2.3.5. Abstraction results for the three flow temperatures are provided in Table 4.1.

Table 4.1: Geothermal well abstraction requirements

	Temp Drop, ΔT	Water extracted	Heat Removal Rate	Max. Well Lifetime
	(°C)	(m^3)	(kW)	(y/km^2)
Geo (75°C)	12.1	120,486	253	657
Geo (65°C)	14	109,425	294	625
Geo (4GDH)	17.2	94,119	359	591

The lower flow temperature abstracts the least volume of water from the aquifer, roughly 15% and 20% less than the flowrates of the higher temperature circuits. However, the temperature drop of the abstracted water and the heat removal rate are also substantially higher. This was due to the higher heat capacity of the heat pump at lower load temperatures. For the 4GDH network, the required HP temperature rise was only 5°C. For each simulation, the temperature drop was significantly lower than the maximum drop proposed previously of 40°C. Therefore, the flowrate could be reduced in each model to extend the well's lifetime to the values shown.

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[v] Which the author has previously investigated.

In terms of the district heating networks, performance metrics are given in Table 4.2.

Table 4.2: Geothermal annual averages and totals

			Hours of Operation		Operating Power				
	Flow Temp	Return Temp	HP	Gas	HP	Gas	HP COP	Total Heat Sent	Total Losses
	(°C)	(°C)	(h)	(h)	(kW)	(kW)	(-)	(MWh)	(MWh)
Geo (75°C)	76.6	52.9	6694	57	364	1056	3.3	2497	350
Geo (65°C)	67.5	44.5	6079	16	398	934	3.9	2435	288
Geo (4GDH)	56.9	34.9	5229	18	449	1007	5	2368	221

Several trends associated with lowered flow temperatures were evident. As with the heat extracted from the aquifer flow stream, the average heating power of the heat pump is higher with a lower flow temperature. Although the 4GDH heat pump operated for nearly 22% fewer hours than the 75°C network, it provided a greater proportion of the total heat sent – 99.1% as opposed to 97.6%. This was similarly reflected in the lower usage rate of the gas boilers in the cooler networks. However, the similar gas operating power indicated that the boilers were utilised in each as a peaking technology.

Further benefits of lowering the temperature were an attendant improvement in the COP of the central geothermal heat pump and lower distribution losses. These two benefits, highlighted in the last three columns of Table 4.2, are a strong argument for the lowering of temperatures: the efficiency of the whole network is enhanced due to lower losses, meaning less heat must be sent; and the heat pumps efficiency is raised meaning this lower level of sent heat can be produced with a lower level of electrical input.

Distribution Losses

The reduction of distribution losses is a principal aim of low-temperature district heating. The monthly losses from the three temperatures investigated are provided in Figure 4.7. This plot provides the monthly losses in total terms and as a percentage of the total heat sent to the distribution network.

Lowering the flow temperature led to a similar proportional reduction in losses each month. The total losses in summer were lower than winter, however, the percentage of heat produced which was lost during distribution was lowest in winter and highest in summer. The lower flow rates in summer lead to a longer residency time during distribution causing more heat to be lost.

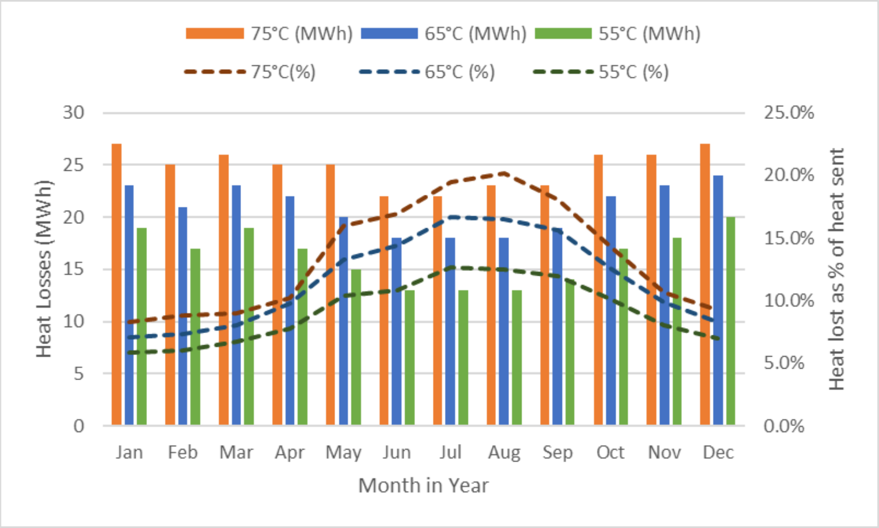

Figure 4.7: Monthly distribution losses across geothermal models

A similar trend was exhibited by losses from the thermal store. The absolute values were similar in each month across the year at approximately 2MWh per month for 4GDH and 3MWh at 75°C. As a percentage of the heat sent they exhibited seasonal dependence, as presented in Figure 4.8. This was due to the lower level of heat demand in summer and the higher average store temperature counteracting the higher average ambient temperatures of this period.

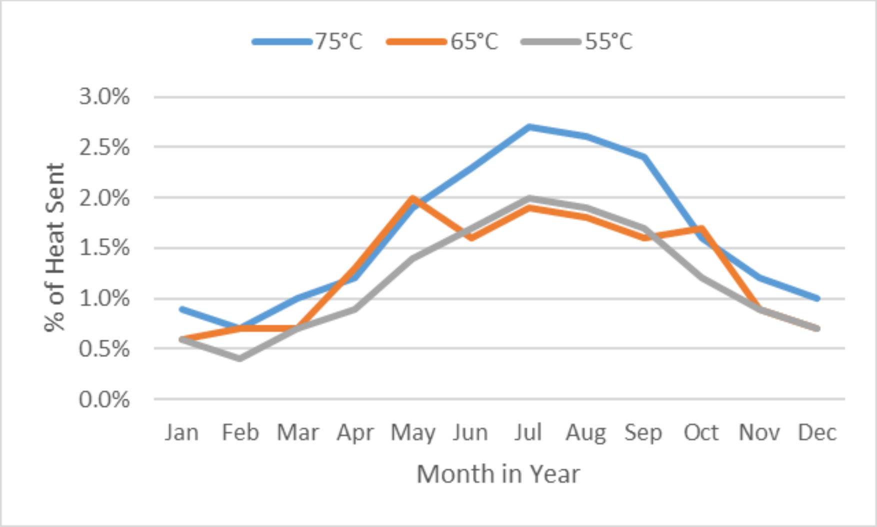

Figure 4.8: Thermal store losses as fraction of heat sent

Fuel Cost and Carbon Content of Heat Produced

The lowered losses in the system have a direct impact on the required energy input to, fuel costs of, and carbon emissions from, the system. Full year results for these metrics are provided in Table 4.3. The lowering of flow temperature produced a scale reduction in each metric with double the temperature drop corresponding to approximately double the savings. Reducing flow temperatures from 75°C to 4GDH temperatures caused a reduction of approximately 40% in each metric.

Table 4.3: Geothermal network performance metrics with reduced circuit temperatures

Metric	Flow Temperature	Heat Source		
		HP (electricity)	Boiler (gas)	Total
Energy Input (MWh)	75°C	744.5	62.9	807.4 (-0%)
	65°C	632.4	16.1	648.5 (-20%)
	55°C	470.9	19.3	490.2 (-39%)
Annual Costs (£000s)	75°C	82.1	2.3	84.4 (-0%)
	65°C	69.7	0.6	70.3 (-19%)
	55°C	52.0	0.7	52.7 (-38%)
Emissions (tCO_2)	75°C	217.9	11.5	229.4 (-0%)
	65°C	186.3	3.0	189.3 (-17%)
	55°C	140.4	3.6	144.0 (-37%)

Although the trends in these metrics across the simulations are fairly elementary, they provide strong evidence of the substantial savings to be made from the reduction of circuit temperatures within district heating systems.

4.2.3. Effect of Single Loads

The modelling of the heat demand as a single load, while necessary for the running of simulations in an acceptable time, was a significant departure from reality. With this approach, all the distribution flow circulated around the full circuit and had to travel to the furthest point of the network. The distance travelled by the heat was considerably greater due to this simplification. The upshot of this is that losses will be higher in a single load circuit.

To assess the potential impact of this, a higher resolution model with three loads was produced. Although the total demand on the network remained the same, the loads were divided into: non-domestic loads near to the Energy Centre, phase one dwellings and live-work spaces; and, the remaining phase two buildings. The flowrate through each branch was controlled as for the previous circuit. The sum of this was imposed on the main distribution line and diverters were used to supply each branch with the correct flowrate.

Splitting or combining the loads impacted the distribution losses in the system. It also had the potential impact of changing the overall operational characteristics of the network. Several operational parameters are presented graphically and tabularly here. In Figure 4.9, the main flow and return temperatures of each model are given over a 24h period.

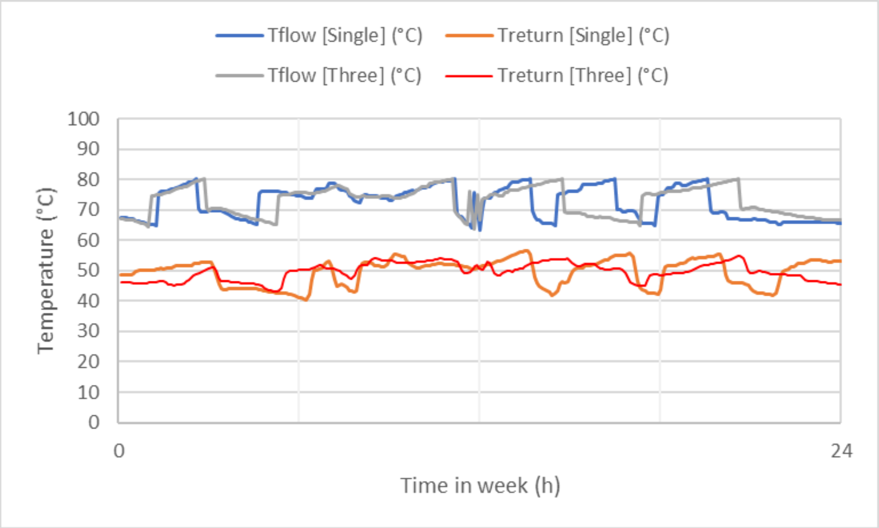

Figure 4.9: Circuit temperatures for single and three load models

Between the models the total distribution flowrate was identical which was expected due to the control used. The shapes of the flow temperature plots were similar for each. During certain periods, the temperatures match closely (from 6am – 12pm) whereas, at other times, the form was similar but shifted in time. The return temperatures were likewise similar in form. Using three loads mitigated the sharp changes in temperature and provided a smoother variation over the day. This likely arose from the mixing of the various flow streams – which were in general at different temperatures – before returning to the supply circuit.

The annual average flow and return temperatures between the models differed by less than 0.7°C. Analysis of the plant and thermal store revealed similar results. Plots analysed of average tank temperature, charging and discharging flow rates, and plant operation exhibited similar forms between the models.

Comparative results from the two simulations are presented in Table 4.4. These results indicated the similar operational performance of the network regardless of the number of split loads present. Hours of operation, average power during operation and heat addition were similar for the plant components. Similarly, the overall heat sent and the losses from the thermal store were similar. The significant difference existed with the pipework losses which dropped by 16% in the model with three loads.

Table 4.4: Performance metrics from single and three load models

	Hours of Operation (h)		Av. Power in Op. (kW)		Heat Addition (MWh)		Total Heat Sent (MWh)	Losses (MWh)		
	HP	Gas	HP	Gas	HP	Gas		TS	Pipe	Misc.
Single Load	6544	29	376	1070	2460	31	2491	32	299	13
Three Loads	6440	32	374	1022	2406	32	2438	32	250	9
% Diff.	-2%	10%	-1%	-4%	-2%	3%	-2%	0%	-16%	-31%

Using a single load for all the simulations means that, while in total terms the results were somewhat inaccurate, they provide a relative comparison of performance. As the pipe modules in TRNSYS do not consider the thermal interaction of adjacent buried flow and return pipes, the losses would be erroeous even if all loads were successfully modelled individually.

A further concern with the loads is that the arriving water is at sufficient temperature for the building plant to successful operate and produce adequate heat. This is particularly true for the furthest building in a network where the temperature drop from the heat source is highest. Table 4.5 presents results on this.

Table 4.5: Delivery temperatures

		Single Load	Three Loads		
			Load 1	Load 2	Load 3
Average Supply Temperature	(°C)	69.8	71.9	70	68.9
Minimum Supply Temperature	(°C)	51	46.6	42.9	44
Hours under 55°C	(h)	1.9	1.3	0.8	1

The supply water temperature lowered more the further from the heat source the load was located. An average difference of 2°C between the closest and furthest load existed. The average supply temperature of the single load existed between these values. The minimum supply temperature (across the whole year) was significantly lower for each of the three loads than for the single load. This was due to the heat capacity contained in each load branch being smaller with the split loads. This meant that small errors in the flowrate control expressed themselves as significant temperature drops. Conversely, the time when the supply temperature was below 55°C is higher for the single load than the split loads. This highlighted the more extreme changes in return temperature which were indicated by Figure 4.9. Overall the time spent with a supply temperature under 55°C was minimal in both models, for all loads.

4.3 Ultra-Low Temperature District Heating Network

In this section results from the ULTDH networks are presented. To begin, the operation of the various subsystems which comprised the models are discussed. After, the same performance metrics from Section 4.2 are presented and discussed.

4.3.1. Behaviour of Auxiliary Systems

Modulated Heat Pump

The work-around modulated heat pump supplied approximately the correct amount of heat so as to elevate the return water temperature to the desired flow temperature of 45°C. As the flowrate of the main distribution circuit was determined by the loading on the system, this was the only way to match supply and demand without recourse to thermal storage and the arrangement of the previous networks.

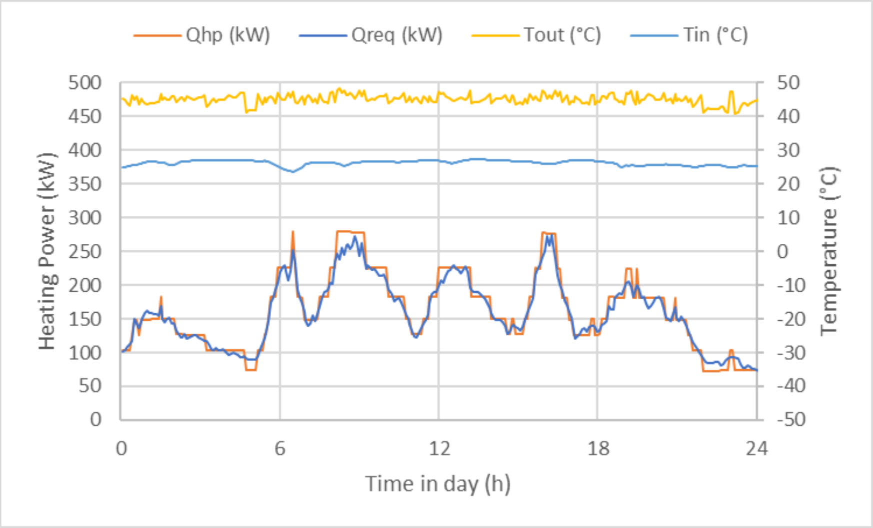

Figure 4.10: Modulated heat pump operation

The operation of the heat pump (similar in both ULTDH networks) is presented in Figure 4.10. The blue line presents the ideal heat addition that would raise the distribution water to exactly 45°C. The orange plot gives the aggregate heating profile from the ten heat pump stages. The modulated heat followed the overall progress of the ideal heat. This resulted in the flow water being raised to roughly the correct temperature. However, as the two values rarely coincided the outlet temperature fluctuated over the range of 40-50°C. This necessitated the addition of a subsequent heating and cooling module.

Space Heating Circuit

The space heating circuit was common to both ULTDH systems and utilised a constant effectiveness heat exchanger to transfer heat form the network to the load. The mass flowrate was tightly controlled on the heating circuit side to ensure adequate heat delivery. The branch flowrate from the district network to the heat exchanger was controlled to provide sufficient heat transfer in the heat exchanger. Plots of its behaviour are provided in Figure 4.11.

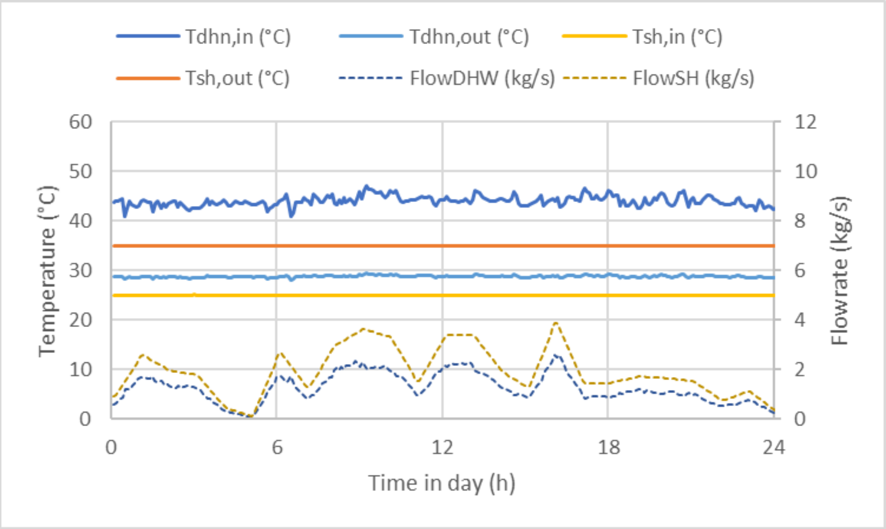

Figure 4.11: Operation of ULTDH space heating circuit

The temperature of the waste stream (Tdhn,out) was higher than is desired for a ultra-low temperature network, causing greater losses from the return pipework. To control the space heating outlet temperature, it was necessary to moderate the district heating mass flowrate such that the following effectiveness equation was satisfied:

$$Q_{t,HE} = \varepsilon Q_{max} \qquad \text{Equation 9.}$$

$$\Rightarrow \ \dot{m}_{SH} \cdot 4.19 \cdot \left(T_{SH,out} - T_{SH,in}\right) = \varepsilon C_{min}\left(T_{DHN,in} - T_{SH,in}\right) \qquad \text{Equation 10.}$$

The district heating mass flowrate only appears in Equation 5 when $\dot{m}_{DH} < \dot{m}_{SH}$ and so this was a control requirement. However, the temperature drop of the hot stream was then limited by Equation 11.

$$T_{h,o} - T_{h,i} = -\varepsilon \cdot (T_{h,i} - T_{c,i}) \qquad \text{Equation 11.}$$

According to Equation 11, with an effectiveness of 80%, a circuit temperature of 45°C and a space heating return temperature of 25°C, the temperature drop across the hot-side of the heat exchanger was limited to $\Delta T = -16°\mathrm{C}$.

Electric Booster Heating

The domestic hot water circuit in the electric-boost heating network operated on the same heat exchanger principles as the space heating circuit. As it was desired to maximise the outlet temperature of the cold domestic hot water stream, the temperature of the hot side could be lowered further. The target outlet temperature of this waste stream was 25°C to provide a 20°C drop across the heat exchanger. This was done to ensure a low return temperature and to simplify the control applied.

It was assumed that the DHW entered the heat exchanger for pre-heat at 10°C (the annual average ambient temperature) and was subsequently raised to 50°C by the auxiliary heater. Figure 4.12 provides a representative plot of pertinent temperatures and heating rates in the domestic hot water circuit.

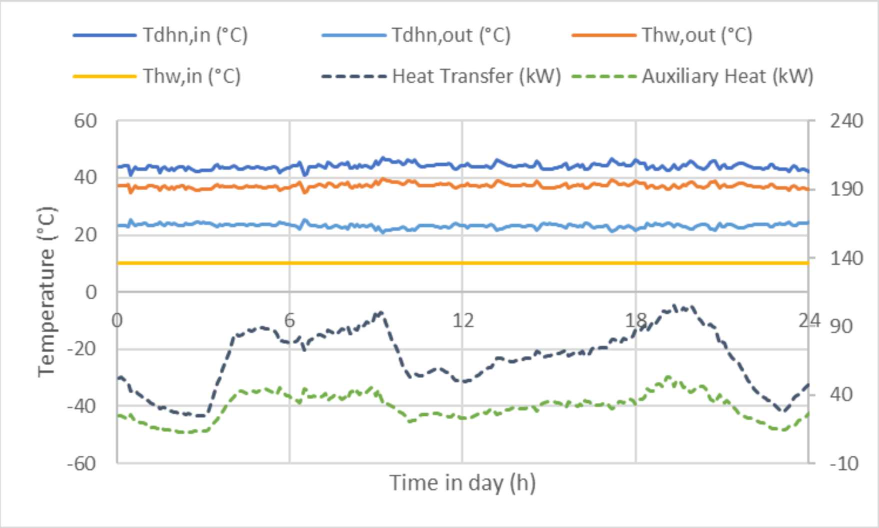

Figure 4.12.: Operation of electric boost heating circuit

Booster Heat Pump

The evaporator and condenser streams of the booster heat pumps were both extracted from the main district heating network. The heat pump raised the temperature of the ‘heated’ stream by transferring heat from the ‘cooled’ stream. The heated stream was then passed to a heat exchanger located in a dummy thermal store for the instantaneous production of DHW. The thermal store removed the requirement for heat pump modulation. The outlet of the heat exchanger formed a second waste stream which, alongside the cooled waste stream from the heat pump returned to the district heating network. The temperature profiles of these flows are provided in Figure 4.13.

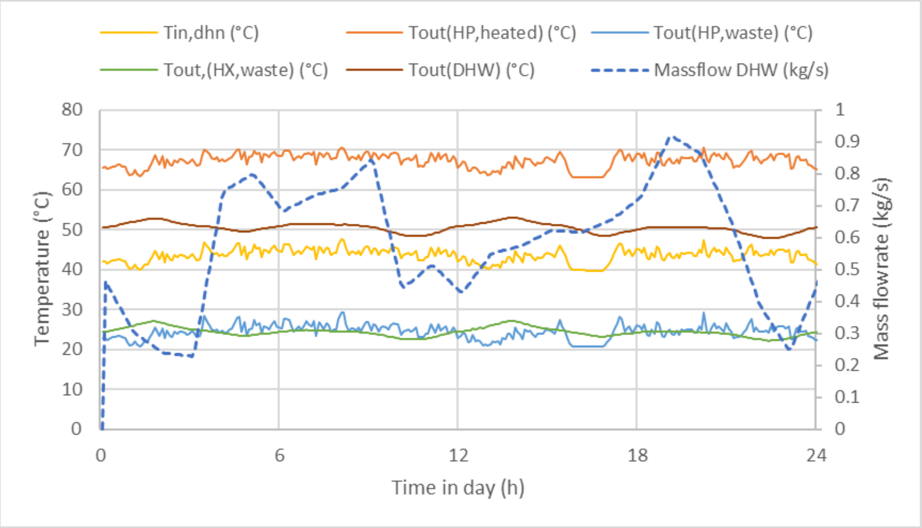

Figure 4.13: Booster heat pump operation

Although the outlet temperature of the domestic hot water varied around 50°C this arose from the lack of modulation of the heat pump. Furthermore, in a real system, the heat pump would be situated at every (or most) building and so would not require less modulation when operated. The dummy thermal store balanced the varying domestic hot water demand (shown in dashed blue) with a constant output heat pump. The central requirements of this circuit were DHW at 50°C, waste flows at 25°C and no supplementary heating or losses. This was achieved by the thermal store work-around.

4.3.2. Performance Metrics

Performance metrics are provided in Table 4.6 relating to the central plant and distribution circuit. The average flow and return temperatures of both networks were close to the target circuit temperature of 45/25°C. This indicated that the higher than desired return temperature from the space heating heat exchanger did not significantly alter the networks operating characteristics. The modulated central heat pump provided over 97% of the total heat sent in each network. The supplementary gas heater provided the remaining 3% while the cooling module, while necessary, removed under 0.1% of the heat sent – equating to roughly 2MWh for the circuit with electric boost and only 5.7kWh for one with booster HPs.

Table 4.6: ULTDH networks' annual averages and totals

			Hours of Operation		Operating Power				
	Flow Temp	Return Temp	HP	Gas	HP	Gas	HP COP	Total Heat Sent	Total Losses
	(°C)	(°C)	(h)	(h)	(kW)	(kW)	(-)	(MWh)	(MWh)
ULTDH+Elec	45.1	26.5	8681	183	235	334	5.6	2099	151
ULTDH+HP	45	26.7	8683	159	258	365	5.7	2297	154

The central heat pumps operated nearly constantly with only short periods in summer when they were off. As a supplementary heater, the gas boilers operated at low capacity predominantly over periods in the heating season. The average annual COPs for the heat pumps were 5.6 and 5.7 respectively. The maximum and minimum values over the year for both systems were 5.9 and 5.2, respectively. These high values were attained due to the low circuit temperatures used and the relatively stable temperatures of the abstracted river water annually.

The total heat sent in the electric boost network was lower than the total annual demand because a substantial amount of the heat was generated at the buildings and not by the central plant. This explains the low average power of the heat pumps which in the case of the electric boost network was lower than the annual average demand.

Performance metrics for the building located plant are presented in Table 4.7. Although the flow temperature of the DHW in the booster heat pump system fluctuated in the performance plot (Figure 4.13), the average value across the year was close to the target of 50°C. This provided some confidence that the performance and sizing of the heat pump was appropriate. The use of a dummy thermal store required the outflow temperature of the heat pump to be approximately 67°C. If better control was applied such that the outflow from the HP was 55°C, then its COP may be better than the 5.2 reported here due to the lower temperature differential.

Table 4.7: ULTDH networks' building plant performance metrics

	Waste Streams			DHW Production				
	SH	DHW1	DHW2	DHW Temp	Heat from DHN	Aux. Heat Added	COP	Heat for DHW
	(°C)	(°C)	(°C)	(°C)	(MWh)	(MWh)	(-)	(MWh)
ULTDH+Elec.	28.8	23.3	0	50	583.2	272.8	1	856
ULTDH+HP	28.8	25	24.5	50.9	780.5	92.7	5.2	873.2

The total heat required for DHW varied slightly between the two circuits due to the higher average flow temperature in the booster heat pump system. Of the heat requirement for DHW in the network with electrical booster heating, 68% originated from the district heating network while 32% was provided by the electrical element. The equivalent values for the network with booster heat pumps were 89% from the district heating network and 11% from the heat pumps electrical input. The energy from the district heating network arose from a combination of the heat already contained in the heated stream, and the heat transferred into it from the cooled stream. Each contributed 50% of the heat transferred from the district heating network.

Distribution Losses

In both networks, a portion of the heat for DHW was produced at the buildings and therefore the total heat sent from the central energy centre was lower. In Figure 4.14, losses from the distribution network are presented by month as total values and as percentages of the energy sent.

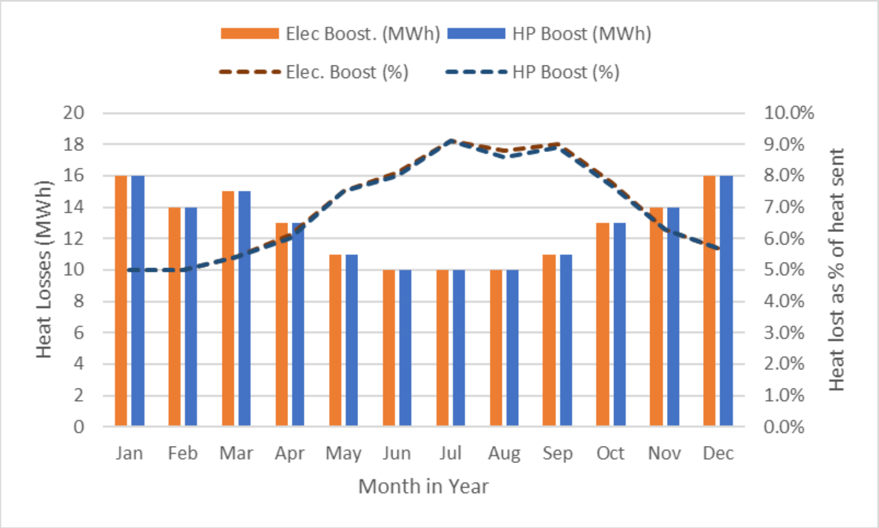

Figure 4.14: Monthly distribution losses from the ULTDH networks

The monthly distribution losses follow the same trend as presented in Figure 4.7, with lower overall losses but higher percentage losses in summer against winter. As the circuit temperatures and flowrates in both the low temperature networks were similar, the overall losses do not vary significantly between the two networks. From April to October inclusive, the total losses from the circuit with booster heat pumps were 0.1-0.2MWh greater than the electric heating circuit. This was due to the higher demands for DHW as a proportion of total heat demand and the corresponding higher quantities of central heat produced by the system with booster heat pumps.

ULTDH Fuel Costs and Carbon Content of Heat Production

In Table 4.8, the annual energy produced by the systems, and the associated fuel costs and carbon emissions are presented. This includes a breakdown of the centrally and locally produced heat.

Table 4.8: ULTDH networks' costs and environmental impact

Metric	System	Heat Input			Total
		Electricity (Central HP)	Gas (Boiler)	Electricity (Aux. Heat)	
Energy In (MWh)	ULTDH+Elec	373.5	64.3	272.8	710.6
	ULTDH+HP	401.8	61.3	92.7	555.8
Fuel Costs (£000s)	ULTDH+Elec	41.2	2.4	30	73.6
	ULTDH+HP	44.3	2.3	10.2	56.8
Emissions (toCO_2)	ULTDH+Elec	113.5	11.8	78.3	203.6
	ULTDH+HP	120.7	11.3	26.2	158.2

For each metric, the system with booster heat pumps had values 22-23% lower than the system with electric heating. This arose directly from the use of electricity in both systems to provide supplementary heating for DHW and the high COP (of roughly 5) that the booster heat pumps had compared to the direct electric heating which was assumed to be 100% efficient i.e. a COP of 1. This can be seen with reference to the total energy in, where the extra energy required at the central HP of the system with booster heat pumps (28.3 MWh) was considerably less than the extra energy required by the auxiliary heater in the network with electrical boost (180.1 MWh).

4.4 Chapter Summary

This chapter presented the main findings from the TRNSYS simulations conducted. The reduction of circuit temperatures was first investigated. These were lowered from 75°C to 4th generation temperatures. The overall operation of the networks was not affected by this. However, many key performance metrics improved with lower circuit temperatures. In particular, 40% reductions in energy input, cost and carbon emissions were possible by reducing to 55°C. The COP and distribution efficiency of the network also improved with this temperature drop across the year.

The results of the ULTDH model indicated that ultra-low heating could be achieved, provided auxiliary heat plant was installed in buildings for the generation of DHW. The distribution losses in these networks reduced even further than the 4th generation network. However, in terms of cost and carbon emissions the ULTDH networks were less appealing than 55°C networks. The financial position of each network will be analysed further in the next chapter to supplement the performance assessments here.

A limitation of the models developed was shown to be the aggregation of all loads into a single load. This was necessary with the software selected but posed an issue with the accuracy of the results. Although the models roughly agreed, details of the performance revealed by the multi-load model were absent in the single load one. The operation of each network also displayed subtle differences.

Chapter 5: System Finances

Having investigated the performance of the models and reported upon some of the key performance metrics, a comparison between all systems will be presented in this section. This takes the form of a financial comparison, where a full analysis of the capital and operational costs, alongside revenue streams, will allow the annual cost of energy to be determined.

5.1 Costs and Revenues

In Sections 4.2.2 and 4.3.2, the operational costs arising from fuel consumption were presented. In this section, a financial analysis will be conducted considering all capital and operational costs and revenues generated from RHI payments.

5.1.1. Capital Costs

The capital expenditure (CAPEX) of each network is based on the benchmark values in Table 3.1, Section 3.3.3. Some of the costs are common to all the networks e.g. the buried insulated pipework, HIUs and heat substations, whereas others are individual. Using the total insulated pipe length of 2600m, the capital cost is approximately £1.217m. Alongside this it is assumed that for every network HIUs will be installed in every dwelling and that 10 heat meters/substations will exist across the site – at the entrance to non-domestic buildings and at junctions in the network. The costs associated with these are £0.254m and £0.033m, respectively.

For the geothermal network the cost of the geothermal well has been provided at £8m. The heat pump and back-up gas boilers, with capacities of 320kW and 1200kW, respectively, incur a capital cost of £0.278m. Finally, the thermal store, which was assumed to have a volume of 50m^3 would cost approximately £0.054m.

The ultra-low temperature networks require an extra 3000m of buried pipework to convey the abstracted river water to site, costing approximately £1.404m. The central heating plant is common to each. With installed capacities of 460kW (HP) and 500kW (Gas) this plant costs approximately £0.345m. It is assumed that the electric boost heater could be easily incorporated into the HIU at minimal extra cost. The booster heat pumps had a capacity of 37.4kW in the TRNSYS models. However, this appears low for a system with distributed heat pumps. Instead, it is assumed that 100kW of booster heat pumps are required at a cost of £0.070m. The total capital costs are presented in Table 5.1.

Table 5.1: Total CAPEX for the networks

Network	Heat Source Access (£m)	Plant Cost (£m)	Miscellaneous Cost (£m)	Total Cost (£m)
Geothermal	8	1.836	0.984	10.82
ULTDH + Elec	1.404	1.849	0.325	3.578
ULTDH + HP	1.404	1.919	0.332	3.655

This costing does not take explicit account of the myriad ancillary systems required by the network or the development costs incurred in the planning stage. A generic cost of 10% has been included to represent these costs. The high capital expenses associated with the geothermal borehole and the various buried pipework will likely dwarf these costs anyway. A breakdown of the costs is presented in Figure 5.1.

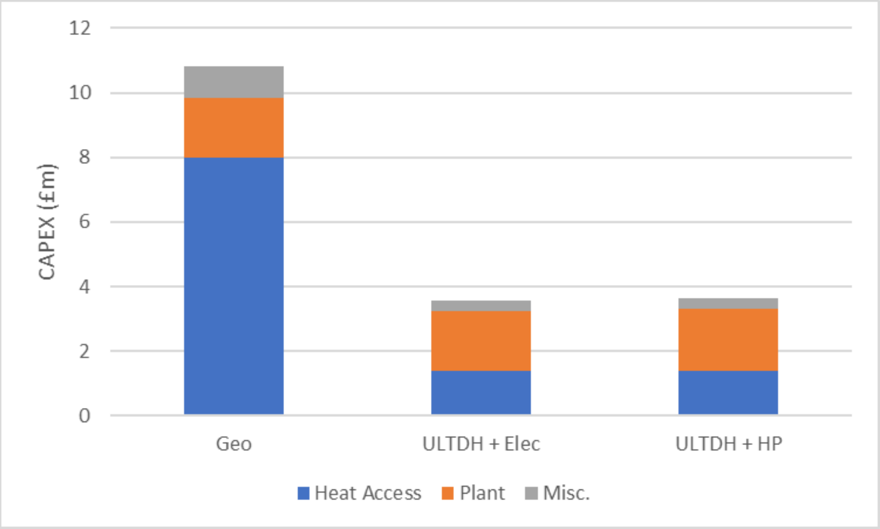

Figure 5.1: Breakdown of networks' CAPEXs

5.1.2. Operational Costs

There are several continual operational costs associated with each system. The energy input costs to the heating plant were provided previously. Alongside these are licensing costs associated with the abstraction of groundwater, annual maintenance and personnel costs, and the costs of pumping the fluid around the circuit.

Generic

These generic and maintenance costs were calculated based on energy produced with respect to the values presented in Table 3.1. The cost figures for each network are provided in Table 5.2.

Table 5.2: Generic annual OPEXs

Network	Heat produced (MWh)	Maintenance (£)	Staffing and Rates (£)
Geo (75°C)	2497	32,500	57,200
Geo (65°C)	2435	31,700	55,800
Geo (4GDH)	2368	30,800	54,200
ULTDH + Elec	2099	27,300	48,000
ULTDH + HP	2297	29,900	52,600

Pumping Requirements

For each circuit, the annual quantity of energy required to circulate the heat carrier around the network was determined. As the systems' pipework and hydraulics have been simply designed for the models, it was decided to only assess the pumping requirements to overcome the major head losses in the system i.e. those arising from pipe-wall friction and not from components.

Although water's density and viscosity vary significantly across the temperature range in the circuit, it was found that the friction factor, f, was effectively constant across every simulation. For each simulation the flow and return friction factors were determined based on the average temperature over the whole simulation of the flow and return pipes, respectively. These were then used to calculate the pressure drop and pumping power using Equation 12.

$$W_{pump} = \dot{V} \cdot f \cdot \left(\frac{L_{pipe}}{D_h}\right) \cdot \frac{\rho \cdot v^2}{2} \qquad \text{Equation 12.}$$

The annual energy required for pump work was then determined and the results are presented in Table 5.3. Lowering the circuit temperature increased pumping requirements via two mechanisms. First, the density of water increases as its temperature drops which increases the pumping power according to Equation 12. This is evidence by the geothermal model results where the average mass flowrates were equal, but the pump energy increased at lower temperatures.

Secondly, the overall circuit temperature differential is inversely proportional to the mass flowrate for a given amount of delivered energy. Although the planned differential in each model was the same (ΔT=20°C), in practice it was lower for the ULTDH networks. A corresponding increase in the average flowrate and flow speed led to a twofold increase in the energy consumed by the pump.

Table 5.3: Energy consumed through pump work

	Circuit Averages					Pipe Friction		Annual Pump Energy
	$\dot{m}_{flow}$	v_{flow}	T_{flow}	T_{return}	ΔT	f_{flow}	f_{return}	
	(kg/s)	(m/s)	(°C)	(°C)	(°C)			(MWh)
Geo (75°C)	2.92	0.32	75.4	53.6	21.8	0.2802	0.2802	20.9
Geo (65°C)	2.92	0.32	66.5	45	21.5	0.2802	0.2803	21.1
Geo (4GDH)	2.92	0.32	56.2	35.2	21	0.2802	0.2803	21.9
ULTDH + Elec	3.25	0.36	44.5	26.7	17.8	0.2802	0.2803	40.9
ULTDH + HP	3.56	0.4	44.5	26.9	17.6	0.2802	0.2803	43.5

Lowering the flow temperature beyond what has been done here would begin to impact the maximum temperature differential possible. For example, a minimum outflow temperature from the heat exchangers of 15-20°C could be imposed by ambient conditions meaning that under supply temperatures of 35-40°C, the maximum temperature differential is under 20°C. A detailed investigation into the trade-off between temperature differentials and flowrates with reduced circuit temperatures was not a part of this project, however, this could form the basis of future work.

SEPA Subsistence Charge

A further operational cost would arise from charges imposed by SEPA for the abstraction of groundwater. All networks are subject to this and the cost was calculated according to Equation 13 (SEPA, 2015).

$$Sub = V_a \cdot L_o \cdot L_e \cdot S_o \cdot S_e \cdot P_a \cdot N_a \cdot F_a \qquad \text{Equation 13.}$$

Table 5.4 presents the definition and value for each of these factors. Both the geothermal and river abstractions fell into categories with identical factors so the subsistence charges for each network is equal.

Table 5.4: Subsistence charges for abstractions (SEPA, 2015)

Factor	Definition	Value	Criterion
V_a	Volume abstracted (daily)	1.0	101-2000m^3/day
L_o	Loss factor (% abstracted lost)	0.3	95% return
L_e	Length affected factor (distance between abstraction and discharge)	0.2	<500m
S_o	Source of abstraction	1.0	Inland
S_e	Seasonality	1.0	All year
P_a	Proportion of flow	0.95	<10% of 95th percentile
N_a	No. of abstractions	9.4	>100
F_a	Financial	£1185	
Sub		£635	

5.1.3. RHI Payments

All networks modelled are eligible for payments under the non-domestic renewable heat incentive. Any geothermal heat installations (over 500m depth), and heat pumps with a design COP and SPF of 2.9 and 2.5, respectively, are eligible for payments (Ofgem, 2018). As the modelled systems are deemed ‘complex’ the payments are determined according to Equation 14.

$$Pay = Tariff \cdot HUEP \cdot \frac{HGBI}{THG} \qquad \text{Equation 14.}$$

Where $Tariff$ is the appropriate tariff provided previously in Table 1.1; $HUEP$ is the heat used for eligible purposes – which consists of all heat delivered here; $HGBI$ is the total heat generated by the accredited installation; and, THG is the total heat generated by plant in the system. Although payments are calculated and paid quarterly, for this analysis, a total annual payment was determined.

All eligible heat is paid at the same tariff for the geothermal network (at 5.38 p/kWh). The RSHP operates on a two-tier basis, where heat produced up to a point is paid at the higher Tier 1 tariff, while remaining heat produced is paid at the Tier 2 rate. The threshold of these rates is the energy produced by the heat pump operating at full capacity for 15% of the year.

The modulated heat pump used in the ULTDH models had an installed capacity of 460kW. Therefore, the Tier 1 threshold was 604.4MWh. The Tier 1 and 2 tariffs for heat pumps are currently 9.36 p/kWh and 2.79 p/kWh, respectively. A summary of the values used in Equation 14 and the annual RHI payment for each system is presented in Table 5.5.

Table 5.5: Annual RHI payments

Network	HUEP	HGBI	THG	Eligible Heat	Tier 1 Fraction	Annual Payment
	(MWh)	(MWh)	(MWh)	(MWh)	(%)	(£)
Geo (75°C)	2146	2437	2497	2094	100	112,657
Geo (65°C)	2146	2419	2435	2132	100	114,701
Geo (4GDH)	2146	2347	2368	2127	100	114,431
ULTDH+Elec	2219	2040	2372	1908	31.7	92,971
ULTDH+HP	2219	2333	2390	2166	27.9	100,135

An operational cost breakdown and the revenues from RHI payments are presented in Figure 5.2. This provides an insight into the annual financial balance of each network.

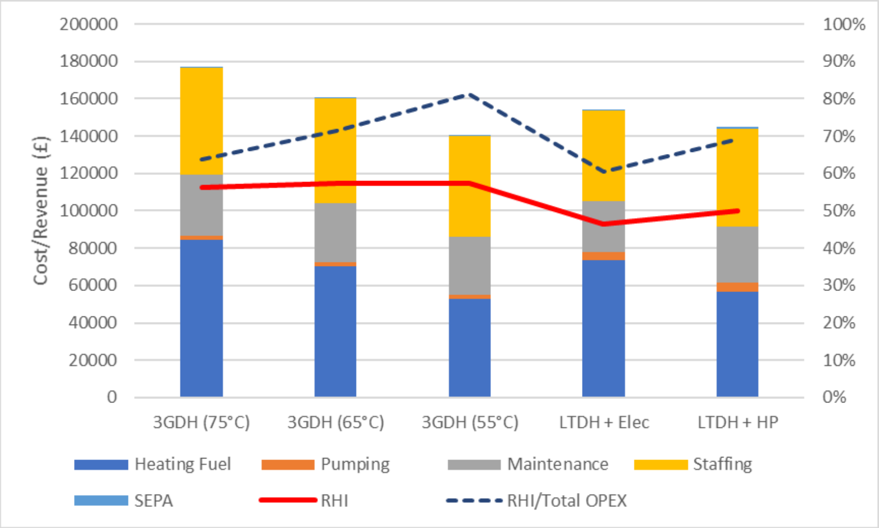

Figure 5.2: Breakdown of OPEX and RHI revenue

It must be noted that roughly 50% of all operational costs arise from network maintenance and staffing. These values were based on benchmarks which can only be indicative. An error small error in these values may lead to a marked different breakdown of operation costing. It is clear from the plot, however, that both pump energy and SEPA charges are minimal compared to the networks’ fuel costs. The increased costs of pump work in the ULTDH networks are marginal compared to the saved fuel costs.

Figure 5.2 also presents the percentage of operating costs covered by RHI payments. This is highest, at over 80%, for the geothermal network at 4GDH temperatures. The ULTDH network with electrical boost heating has the lowest coverage due to the large percentage of heat demand met through non-eligible generation.

5.2 Financial Metrics

To end this section on the proposed networks' finances, two comparative metrics will be presented. These relate to the annual costs associated with producing heat, and the likely returns and payback period of the capital expenditure.

5.2.1. Cost of Energy

Here the annual cost of energy is defined to be the total operational costs in a year divided by the total useful energy delivered in that year. The Levelised Cost of Energy is arguably a more appropriate metric for assessing the total lifetime cost of producing energy. However, it entails consideration of all lifetime costs, including those dependent commodities with volatile and variable prices. This advanced analysis is therefore beyond the scope of the current project.

Figure 5.3 presents the cost of energy for each system. Two plots are shown, one with the total cost of energy as defined above, and a second, with the cost of energy after RHI payments have been considered. This provides an indication of the minimum required price to meet the running costs only annually.

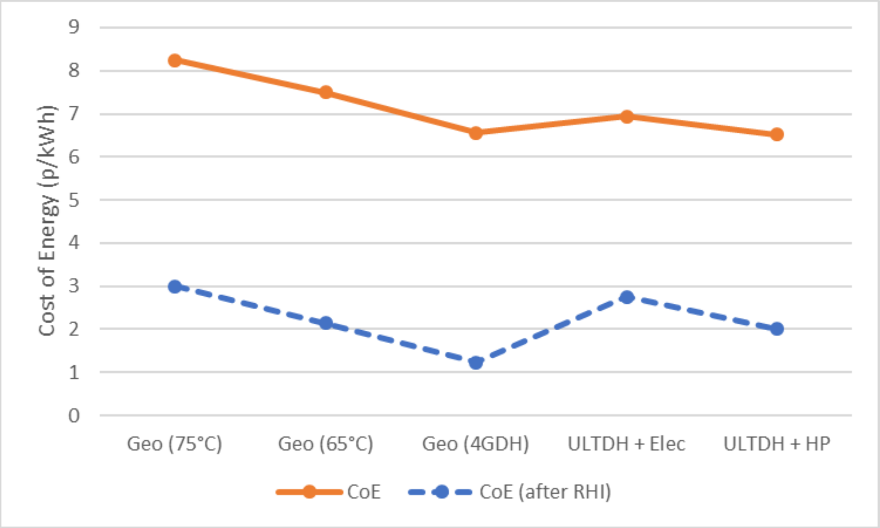

Figure 5.3: Cost of energy for each network

Comparing the networks, there is a clear trend of lower cost of energy with decreasing flow temperature. However, the geothermal network at 4th generation temperatures has the joint lowest cost of energy alongside with the ULTDH network with heat pumps. Considering RHI payments, it has by far the lowest cost of energy at just over 1.2p/kWh.

As a comparison, the total cost of energy from a gas boiler in a modern, small flat was estimated to be 10.24 p/kWh (DECC, 2015). Against this value, all the proposed systems are highly competitive and are cheaper by at least 2 p/kWh. Interestingly, the cost of energy from the *Heat Networks* report without boiler costs was 4.57 p/kWh. It is the low utilisation of the boiler, and the high maintenance capital costs that increase the price. This further strengthens the case for district heating networks supplying modern flats, as the maintenance and plants costs are shared between all users.

5.2.2. Break-Even Point

The second metric is the time taken to payback the initial project capex. The OPEX analysis did not consider the interest repayable on any loans as it was assumed that a complex funding, subsidy and grant package could be secured for these networks. In Figure 5.4 the total revenues are presented alongside the CAPEX payback period. Revenue from heat sales was calculated using the 10.24 p/kWh presented above.

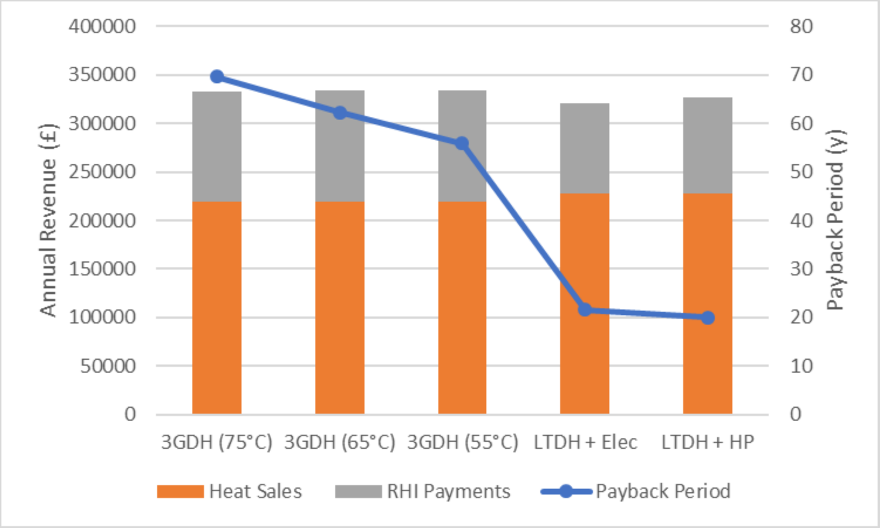

Figure 5.4: Network revenues and break-even points

The periods are markedly different between the geothermal and RSHP networks. This is to be expected due to the higher CAPEX associated with the former. This makes a comparison of the networks according to these networks somewhat unreliable. However, a trend exists across the geothermal systems such that the payback period decreases with lowered flow temperature. A further consideration is the network lifespans. If they were designed for 25 years, then the geothermal networks are uneconomical. However, the resource of these networks may last for over 500 years as shown in Section 4.2.2. With operational lifespans over a century the long payback period may be less significant.

5.3 Chapter Summary

A financial assessment revealed the substantial capital expense associated with each of the modelled networks. This arises from the installation of the network plant but also the additional cost of accessing the heat resource for exploitation. The major operational costs were shown to be for fuel requirements, maintenance and staffing although the later costs were based solely on benchmarks. RHI payments improve the economics for all networks and would cover between 60 and 80% of operational cost across the networks.

The cost of energy was calculated as a simple metric which allows comparison of the economics of various technologies. Compared to the average UK cost of heat from gas burners, every network was found to be cheaper. If RHI payments were deducted from OPEX then the cost of energy could lower to just over 1p/kWh for the 4th generation network. Due to the very high capital costs associated with these networks, the payback periods were roughly 20 years for the RSHP and 60 years for the geothermal well. The markedly different capital costs influence these results and it was noted that the repayment period may be less important when the operating lifespan of a technology far exceeds it.

Chapter 6: Discussion

6.1 Key Project Findings

The aims of this project were to assess the demand and supply options for a DHN at an urban regeneration project; to investigate the performance, financial and environmental impacts of reducing temperatures to 4GDH levels; to determine the relative performance of low and ultra-low temperature district heating networks; and, to investigate and appraise the TRNSYS simulation tool for conducting such analyses. In this section, each aim is discussed in turn and the relative success of the project is analysed.

Heat Demand

As a prerequisite for district heating network design, the accurate quantification of heat demand and available heat resources at the site were determined. The project's heat demand was assessed by reference to benchmark consumption values and representative demand profiles. The total values determined were similar to other new builds in Kilmarnock. Therefore, confidence existed in this analysis.

The use of representative demand profiles was a greater assumption. With increasing levels of thermal performance, the operating schedules alongside the total heat demand of buildings is changing. The profiles here were based on dwellings which were relatively old and so there is a significant degree of uncertainty regarding the demand shape at the HALO site.

Best practice dictates that the thermal performance of buildings is assessed through detailed transient simulation. Such an approach can provide both the temporally varying and total demands of a building over arbitrary periods. A lack of data and information meant that this approach could not be taken, and this is the case for many district heating systems where the simulation of multiple buildings presents as an unfeasibly large and arguably unnecessary task.

Resource Assessments

The local renewable supply options were assessed based on the likely extractable heat in each over the year. Although not all resources were investigated, due to scoping considerations, the methods adopted for those that were provided useful results. In particular, the temporal aspects allowed a demand-supply matching exercise to be carried out which highlighted the reliability of each resource.

A high level of uncertainty existed around exact conditions at the location without detailed site investigations. Assumptions had to be made here but the adoption of conservative assumptions throughout produced a lower limit on the likely heat resource. It is arguable, that circuit performance of low-temperature district heating networks is effectively independent of the specific resource utilised. However, for a whole system analysis, inclusion of supply technology was essential.

4GDH vs. Traditional

The effect of circuit temperatures on network performance formed the core of the analyses undertaken. The reduction of the supply temperature from 75°C to the lowest possible without additional plant impacted the performance and financial metrics of the geothermal network considerably. Reducing flow temperatures improved costs and performance according to every metric presented.

In terms of the central plant, 4GDH temperatures required heat pump operation for 22% less time than at 75°C whilst still covering over 99% of total heat supplied. This occurred because the lower return temperatures raised the heat pumps COP from 3.3 to 5. Also, the total losses in distribution dropped by 37%. The upshot of this was that the energy input, fuel costs and carbon emissions all dropped by approximately 38%.

The cost of energy for this system was also lowest of all investigated, at approximately 6.5 p/kWh. When RHI payments were considered, the minimum sale price of energy to break even annually would be just over 1 p/kWh. The results of these analysis demonstrate the significant benefits to be derived from 4GDH temperatures.

Boost Heater

The investigation into ULTDH networks was intended to explore the benefits, if any, of lowering flow temperatures below 4GDH levels. Between the two booster technologies presented, the system with booster heat pumps far out performed the system using direct electric heating.

With respect to every metric, except total distribution losses, booster heat pumps provided greater benefits. In terms of total energy input, running costs and carbon emissions, the booster heat pump system brought savings of 20-22%. Further, its cost of energy, both before and after RHI considerations, and its repayment period were more appealing than the direct electric system. This is the case even though additional plant costs are incurred.

ULTDH vs. 4GDH

The benefits of these systems compared to 4GDH temperature systems is debatable however. The central HPs COP in the ULTDH networks was better than in the 4GDH network – even though the source temperature of the RSHP was lower than that of the geothermal well. However, the booster energy requirements meant the total energy input to the ULTDHN were higher. This directly resulted in a corresponding increase in fuel costs and carbon emissions.

The approach adopted here to use a different resource for each network type perhaps obscures the overall comparison between them. As stated above, the COP of the geothermal heat pump was comparable to the RSHPs COP. However, the former had to produce a temperature rise of 5°C as opposed to an average temperature rise of 35°C in latter. Using the river resource for the 4GDH network, or vice versa, may influence the performance and financial metrics considerably.

An interesting impact of ULTDH networks is the potentially higher circuit flowrates required. This trend impacts the energy requirements for pump work and so introduce a further drawback of these systems. However, the increase in pump work (of roughly 20 MWh) was minimal when compared to the equivalent reductions in distribution losses (ranging from 70-200 MWh).

Optimal Network Design

Overall, the optimal network for the HALO project from the options assessed was the geothermal powered HP operating at 4GDH temperatures. According to nearly all the performance metrics here, it displayed the most desirable values: its cost of energy, carbon emissions and operational costs. The major drawback of this scheme is the significant capital cost associated with the geothermal borehole.

From these findings it was realised that another concept proposed earlier would potential make for a more optimal solution. This is the ULTDH network powered heat transfer from a geothermal well. Although this system would still incur the high capital cost, the operational costs would be significantly reduced due to the removal of the central heat pump. This would capture the benefits of ULTDH while reducing energy inputs. The associated improvement in the annual finances of such a scheme would likely improve the payback period considerably.

TRNSYS Appraisal

All simulation work in this project was conducted on TRNSYS. An aim of the work was to assess TRNSYS' value and suitability for such a task. The 'input-output' approach of the software makes design of models simple with the user perceiving the connections and data flows visually. The ability to use equations based on the outputs of components, allows complex control to be applied to other components. It can be, however, in this respect challenging.

The limited number of components and their simplified underlying mathematics impact the simulated accuracy of the model. For projects with minimal time, the user is constrained by those components which are freely available. However, the in-built capacity to design components from scratch allows the user, with sufficient time and resources, to model the exact system they desire.

A related issue was the model size limitations. This precluded the full network from being modelled and led to the adoption of a significant system simplification, namely the modelling of a single load. The permitted size of the model, can be increased in the source code, however this was not achieved during this project. Even if it had been, a question remains regarding the computational penalty associated with a more detailed system.

Overall, however, the software was highly useful to the commission of the project and allowed all relevant initial aims to be investigated. Its real strength over many other software is the detailed simulation it carries out. The performance of the full system can then be interrogated. The full impacts of operational and control changes can then be determined – something that is not possible on many other software.

6.2 Future Work

This project has answered some important questions regarding the merits of low and ultra-low temperature district heating in the Scottish context. However, it has also brought multiple more questions to mind. In this penultimate section, a few of the most important questions for future work will be presented.

Full dynamic modelling of representative buildings from HALOs housing stock should be undertaken. This would reveal and remedy any errors made in the benchmarking approach here. It would also allow the impact of different building plant systems on demand profiles to be determined. It is possible to incorporate buildings loads into a TRNSYS simulation although this aspect of TRNSYS was not investigated.

Further analyses should be run utilising the same renewable resource in both types of network. A weakness of this work is the fact that two variables are altered between the two network types (supply technology and flow temperature). To attain a better comparison, both supply technologies should be applied in the other network.

A further model to investigate, is a geothermal well powering a ULTDH network via a heat exchanger. As outlined above the advantages of this concept may make it the optimal solution for HALO Kilmarnock.

Finally, more detailed models comprising multiple loads should be designed and simulated. A large uncertainty exists over the impact of aggregated loads on network performance. As part of this, new components should be designed to properly capture the thermal interaction of the buried pipework so that the distribution losses can be more accurately quantified.

Chapter 7: Conclusions

From all the work of this thesis, there are several important conclusions to be drawn.

First, it is possible to supply reliable and cheap heat for all heating demands at HALO Kilmarnock. The cost of energy of each district heating network was lower than the average cost of energy to heat a flat.

Secondly, many substantial, local and renewable resources exist that could power such a network. More resources, that were not assessed, are equally likely to be suitable e.g. disused mine water.

Thirdly, the lowering of flow temperatures to 4GDH levels improves both the performance and finances of district heating networks. This should be increasingly considered in the future design of UK networks.

Fourthly, the use of electric heating in ULTDH networks is to be avoided in preference of local booster heat pumps, regardless of the additional capital cost.

Fifthly, it is debatable whether lowering flow temperatures below 4GDH levels is desirable. When considering cost and carbon emissions, savings from decreased distribution losses do not offset the requirements of the booster technology.

Finally, TRNSYS is a powerful tool for assessing in detail the performance and operation of simplified district heating networks.

7.1 Key Outputs

The key outputs of the project include:

- A cost-effective and high-performance system design for commissioning at HALO Kilmarnock.
- Demonstration of the benefits arising from lowered circuit temperatures in DH.
- Annual, temporal assessments of renewable resources in the Kilmarnock area.
- Several TRNSYS models. These will be made available on the Energy Systems Research Unit’s website: *https://www.strath.ac.uk/research/energysystemsresearchunit/courses/individualprojects/*

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